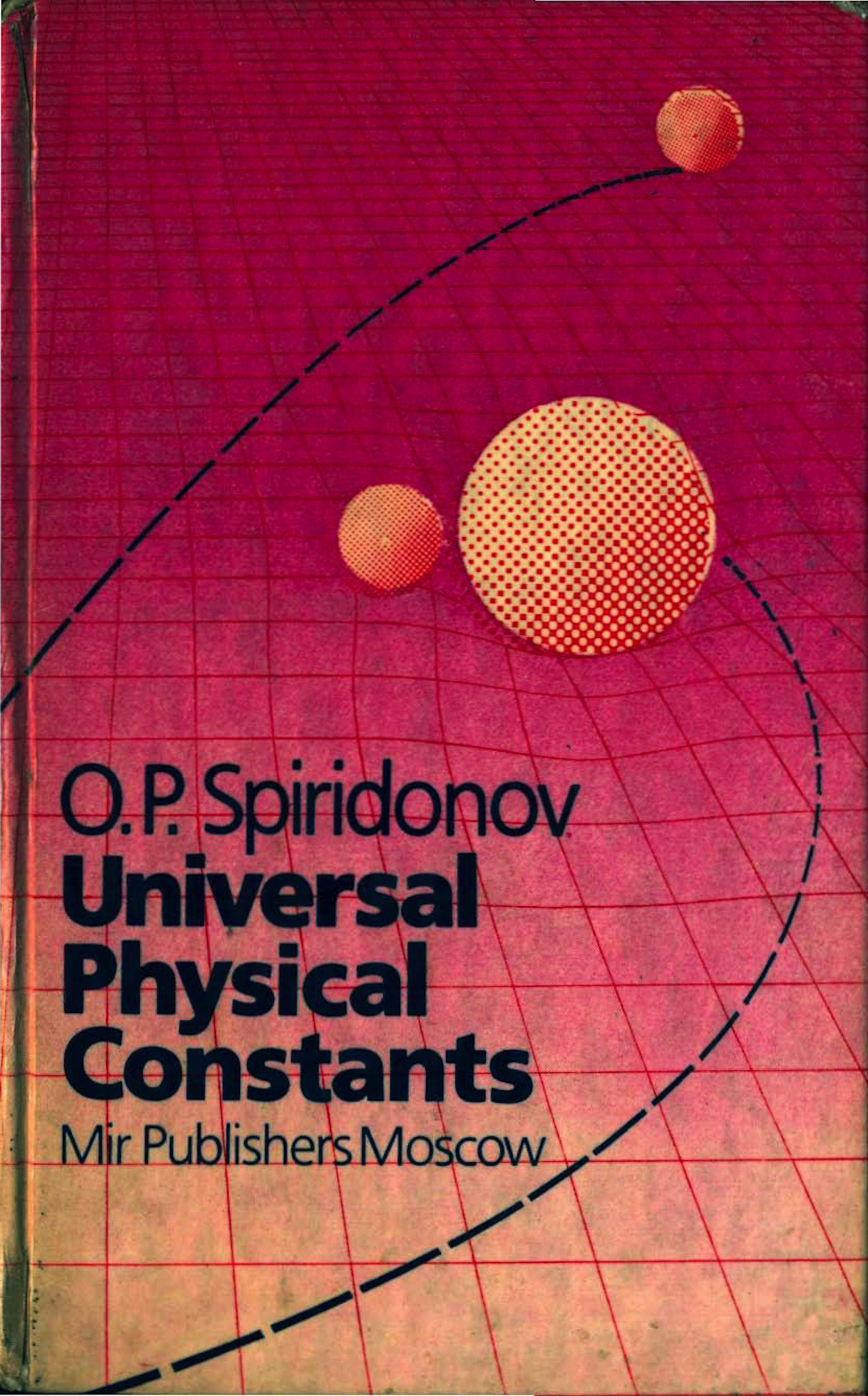

O. P. Spiridonov

Universal Physical Constants

Mir Publishers Moscow

UNIVERSAL
PHYSICAL
CONSTANTS

О. П. Спиридонов

УНИВЕРСАЛЬНЫЕ ФИЗИЧЕСКИЕ ПОСТОЯННЫЕ

«Просвещение» Москва

O. P. Spiridonov

Universal Physical Constants

Translated from the Russian
by Yevgeni Strelchenko

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PREFACE

Hardly anyone can be found for whom the words "universal physical constants" sound entirely unfamiliar. Everyone has some idea of what they are. At least in physics classes—if never afterwards—all of us used them, usually taking them from appendices somewhere at the back of a textbook. However using them as static reference material the student misses their real physical significance and remains unaware of the dramatic events surrounding their discovery. It is the aim of this short popular science book to pay tribute to the universal physical constants.

For, indeed, it is almost impossible to exaggerate the importance of the constants in physics. It does not take too much imagination—to consider them as signposts or milestones erected by Nature along the endless and difficult route to Knowledge.

In the fascinating drama of scientific ideas the physical constants are certainly the leading characters. We shall see that the proper interpretation of the constants and their role often involved a discussion of the central problems of physics, with the participation of the best minds that have advanced science: Newton, Einstein, Boltzmann, Planck and others. These discussions generated new ideas and sometimes completely changed man's world outlook. To measure the constants, as we shall see, most elegant and precise experimental methods were used.

Thus organized around the universal physical constants, the book gives—or so the author hopes—a review of the most significant ideas of modern physics and the first systematic look at the universal physical constants and their role in science. Still, this is not a textbook and the choice of the style and language was first of all dictated by the author's desire to make the material easier for the reader to follow. The reader is not assumed to have a great knowledge of mathematics and all but the simplest equations are therefore omitted. If the book ignites the reader's interest in physics (and what a beautiful science it is!) or whets the appetite for further knowledge, then the effort of writing it will have been worthwhile.

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PROLOGUE

Milestones of Physics

On the highway of physics—a long one and by no means too easy for driving—universal physical constants certainly stand for the milestones. It may take a long time and much effort to cover a mile, but a milestone is seen from far away and each time it gives the driver a feeling of confidence and satisfaction. For certainly there is a long and often dramatic history of well done work behind every one of these natural constants.

Let us have a look now at the heroes of our narrative, as they are presented in Table 1. Some of them bear the names of distinguished physicists who either introduced a particular constant (Planck, Rydberg) or much contributed to its introduction (Avogadro, Boltzmann). Other constants are nameless, but—at least after the book is over—everyone will associate the gravitational constant with the name of great Newton or the speed of light—with the genius of Einstein.

Physical characteristics of the world. In all, there are eleven items in the Table—the most

Table 1

UNIVERSAL PHYSICAL CONSTANTS

Name	Symbol	Value in SI
Gravitational constant	G	6.6720×10^{-11} N·m^2·kg^{-2}
Avogadro's number	N_A	6.022045×10^{23} mole^{-1}
Boltzmann's constant	k	1.380662×10^{-23} J·K^{-1}
Faraday's number	F	9.648456×10^4 C·mole^{-1}
Electron charge	e	$1.6021892 \times 10^{-19}$ C
Electron rest mass	m_e	9.109534×10^{-31} kg
Speed of light in vacuum	c	2.99792458×10^8 m·s^{-1}
Planck's constant	h	6.626176×10^{-34} J·s
Rydberg constant	R_∞	1.0973731×10^7 m^{-1}
Proton rest mass	m_p	$1.6726485 \times 10^{-27}$ kg
Neutron rest mass	m_n	$1.6749543 \times 10^{-27}$ kg

fundamental physical constants known to everyone from high-school physics courses and it is easily seen that they may be broken up into two groups. The first one includes the constants used to describe phenomena of the macro-world. Take the gravitational constant as an example. It enters the law of gravitation and characterizes quantitatively the most important and omnipresent phenomenon of Nature, the gravitational attraction of physical bodies. The gravitational forces govern the motions of astronomical objects, easily observed by naked eye or through simplest telescopes.

The constants of the second group characterize the behavior of the smallest physical particles—such as electrons, protons and the like. These micro-particles cannot be observed directly which, however, does not prevent physicists from studying their properties and laws of motion. *The universal physical constants are the quantities that either characterize micro-objects or enter as coefficients into mathematical expressions of fundamental physical laws.* It should be stressed that all physical constants are objective characteristics of the world surrounding us.

The constants and the unity of the world. Though convenient, the subdivision of physical constants into two groups meets an immediate and very serious objection. The world around us is a single whole and its dissection into the micro- and macro-parts is, of course, artificial. Any macro-object, say a piece of solid, is after all nothing else but a collection of atoms, however great their number may be. The two "worlds" are thus closely interrelated as, no doubt, the two types of constants should also be. In some cases. these relations have been indeed found, in some others — there is a hope to trace them down. For example, attempts are being undertaken to link the gravitational constant (the first one historically) with Planck's constant, our contemporary, indispensable for the description of micro-objects. To find such connections is one of the challenging problems of current physics, and the importance of thorough studies of physical constants for science can hardly be overemphasized.

A little bit of history. It is hardly credible that some time ago physics had no universal constants at all, but those were the times when physics had no highways. The first—gravitational—constant was introduced into physics by Newton, in 1687, and it was not until

1793 that Cavendish measured its value. That was the first entry in the newly-born table of universal physical constants. Since then, generations of physicists worked hard to give the table its present-day form. Some of the constants are relatively young—the charge and mass of the electron, for example, were only measured in 1897. The mass of the neutron came as recently as 1932. The table is being continuously enlarged—following the development of our knowledge of the physical world. A physicist of the 1890's knew nothing about the electron, nor about its charge and mass—nor about atomic physics, for that matter. Today, the structure of the atom is studied in high-school, physics goes ahead and new constants will inevitably come into the table.

Accuracy in determining the constants. You may have noticed, when looking into the table, that the constants are given there with many figures after the decimal point. Isn't it a bit too much of accuracy? At first sight, so it seems. For the speed of light, for example, the author honestly admits to have never used a better value than mere 3×10^8 m/s. And yet, this high accuracy is not superfluous at all. To obtain a figure as precise as possible is sometimes a matter of principle—to distinguish, for example, between a true and wrong theories. A reliable experimentally obtained value of a constant may provide a basis for a new theory. The most spectacular example is, perhaps, given by the classical experiment of Michelson described in our Fourth Story. We shall see its crucial importance for Einstein's theory of relativity.

Are the constants truly constant? Another example comes from more recent times and has to do with the gravitational constant. This constant, as we have already mentioned, determines the motions of astronomical objects and, ultimately, the evolution of the Universe as a whole. The nature of the gravitation, however, is still far from being understood perfectly and a hypothesis has even been advanced that, in the process of the evolution the gravitational constant is changing. This change, however, if at all it exists, must be extremely small and to detect it, very high measurement accuracy is needed. So high, in fact, that it is too early at present to speak of any experimental test.

How accurately we measure physical constants reflects the accuracy of our knowledge of the world and of its properties. No wonder, therefore, that, as time goes on, more sophisticated experimental methods are employed to get more accurate values for the constants. To give the reader a sense of the fascinating world of physical experiment is one of the aims of this book.

For the moment, however, hoping the reader is now intrigued enough, let us start our way—and our book. The milestones of physics, the universal constants, will mark our progress.

FIRST STORY

Strength and Weakness of a Giant or the Tale of Gravitational Constant

It is only natural that a story about fundamental constants should begin with the gravitational constant, the first one ever to come into physics. It was at the end of the seventeenth century that Sir Isaac Newton introduced it to quantitatively describe the gravitational attraction of physical bodies. In the subsequent two centuries, a great amount of observational evidence seemed to erase any possible doubts as to the validity of Newton's theory. Still, there were some problems over the horizon—and the very mechanism of gravitation remained unknown. The next significant development, early in this century, came from Albert Einstein whose genius gave us an entirely new vision of the Universe. Today, with his general relativity theory and with recent astrophysical discoveries, the theory of gravitation and the gravitational constant are again at the center of scientific interest.

GRAVITATION

Surely enough, the phenomenon of gravitational attraction has been known long ago, for one of its forms—gravity—is easy to observe and manifests itself in a variety of ways. We enjoy the beauty of the Niagara Falls and we are unhappy if our favourite vase falls and breaks. Unbearably heavy carrier-bags—isn't this a permanent complaint of housewives? (The word gravity, by the way, stems from Latin *gravis,* meaning heavy). An invisible force holds the Earth's atmosphere near the planet—the sine qua non of our existence. When asked about the reason for all these phenomena, no one would hesitate to attribute it to the all-attracting force of the Earth.

Why is it, however, that apart from gravity we do not usually see any other effects of the gravitational attraction? When talking to each other, for example, we never feel anything actually pulling us together. Two ships sailing in the sea follow safely their courses and do not collide. The reason, of course, is obvious: the gravitational attractive forces are very weak in these cases. Two people at a dinner table attract each other with a force of about only $(1\text{-}3) \times \times 10^{-7}$ N (where N stands for newton, a force imparting an acceleration of 1 $\mathrm{m/s^2}$ to a mass of 1 kg). We can say, in fact, that gravitation is the weakest force that we know in nature. Suppose one compares the electric force that repels one electron from another, with the gravitational force that tends to attract them. It turns out that the electric force is stronger than the gravitational one by a factor of about 10^{42}. The gravitational forces are also immensely weaker than the nuclear forces holding together the constituent particles of the nucleus.

Universal role of gravitation. In the process of interaction of celestial bodies the role of nuclear and electric forces is negligible. Nuclear forces, decrease very rapidly with distance and have virtually no effect outside nuclei. Electrical forces are, of course, felt at large distances ("long range" forces, a physicist would say). But large bodies are electrically neutral, and for this reason have no electrical effect on each other. What determines the strength of the gravitational force is the mass of the body. To get an idea about the figures involved, let us look at some actual examples.

Two 50 kg balls 10 cm apart attract each other with a force of 1.6×10^{-5} N. This is a tiny force. But the Earth ($M_E = 6 \times 10^{24}$ kg) attracts the Moon ($M_M = 7 \times 10^{22}$ kg) by the force of 10^{20} N, being itself attracted by the Sun with the force of 10^{22} N ($M_S = 2 \times 10^{30}$ kg). It is the forces of these tremendous magnitudes that operate in the world of planets, stars, galaxies and supergalaxies. In the deep vacuum of cosmic space these are the forces to determine the evolution of the Universe, our small planet included. No wonder we wish to know about these forces as much as possible.

The gravitational forces between small bodies being weak as they are, the possibilities of studying gravitation in terrestrial laboratories are limited. And, unfortunately, we cannot set up any experiments in the gigantic 'cosmic laboratory' that surrounds us, for there is nothing there that we could change and arrange at our will. Because of the natural limitations, the theory of gravitation stands somewhat by itself in physics. But despite of this the progress in the theory was and is being made. How, when and by whom—this is the subject of the following sections.

GRANDEUR OF GENIUS

Created in the end of the seventeenth century, Newton's theory of gravitation reigned over the minds of scientists for more than two centuries. It was the period when one fact followed another to confirm the theory. Whence the power of the theory? How was the Law discovered?

What is a theory? Or rather, what is the aim of a theory? Well, as far as a physical theory is concerned, the answer should be: in terms of mathematical expressions and equations, to present a quantitative description of observed phenomena. For a newly-born theory to be accepted, two things are necessary. First, the theory should explain experimental facts already established. Second, it should predict some new facts. If the latter are indeed discovered, the theory is considered to be true. This interrelation between theory and experiment is remarkably illustrated by Newton's law of universal gravitation.

The attempts to find out, what actually makes two bodies attract each other, ascend to antiquity. One of the ancient philosophers, Aristotle (384-322 B.C.), classified all bodies as light and heavy. Light bodies go up (like smoke), heavy bodies—say, stones—fall down, for the 'center of the Universe' is their natural goal. For every single body, Aristotle thought, to fall down freely was the most natural thing to do when no force was applied (not that the idea of force was known at the time). He also claimed that light bodies fell slower than heavy ones, as exemplified by a feather compared with a stone (the resistance of the air to motion was then completely unknown). Today, all this sounds like extreme naivety and may only be explained by a low level of ancient science. But Aristotle's authority was such that up to the fifteenth century no one ever dared to challenge his views. Indeed for centuries afterwards, they dominated in science and every single step forward was in fact a deed of scientific courage.

On the way to the Law. Leonardo da Vinci (1452-1519) was the first to question Aristotle's geocentric views. He taught that the Earth resided not in the center of the Universe but in the center of its own elements, close to it and linked with it. But it was Galileo Galilei (1564-1642), the first ever experimenter in physics, who demonstrated a misleading nature of Aristotle's views. What he did was to drop a pair of balls from the top of the famous Leaning Tower of Pisa, Italy. One of them was made of wood, another was a cast-iron cannon-ball, but in spite of the weight difference, both fell onto the ground at precisely the same time. Much as the experiment was simple, it was of extreme importance in the history of science, for this was the first time that a scientific fact was reliably established by *measurement*. "It is not until you have measured a physical quantity that you really can be said to know anything about it." These are the words of Lord Kelvin, the famous British physicist of the nineteenth century.

In the absence of air resistance all objects fall to the earth at the same acceleration independent of their mass—that was the message of Galileo's experiments. He measured the magnitude of "free fall" acceleration which (with some later corrections) turned out to be

$$g_0 = 9.8 \text{ m/s}^2.$$

These facts were the first building blocks for the edifice of Newton's law of gravitation.

Observation of planets produced further experimental evidence for Newton's theory. In Poland, Nicolaus Copernicus (1473-1543) advanced the heliocentric picture of our Solar system (Fig. 1) which postulated the revolution of the planets around the Sun. As to the reason of this motion, he remained unaware of it.

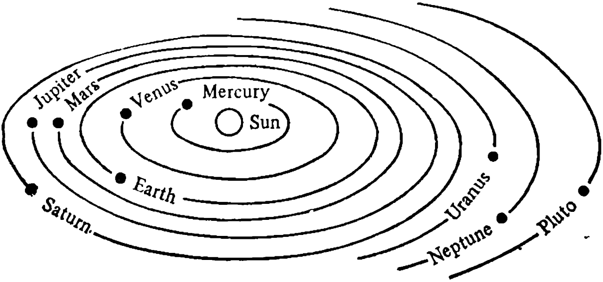


Fig. 1

The next step was taken by Johannes Kepler (1571-1630), the German astronomer. He was able to find mathematical laws which described the motion of the planets.

These laws are not his only achievement. Kepler was the first to suggest that all bodies attract each other with a force proportional to their masses and inversely proportional to the square of the distance between them. Still he did not see any link between the force of gravitation and the behavior of the planets.

With the preparatory work of Galileo, Copernicus and Kepler, the stage was now set for further advancement. A great mind was needed, to mould their ideas, mostly of qualitative nature, into the rigorous mathematical formulation of the law of gravitation. A great courage was needed to recognize gravitation as the force governing the motion of planets. Genius was needed, to endow the mankind with the laws of this motion—the laws of dynamics. But these were the qualities possessed by Sir Isaac Newton (1642-1727). And still another remarkable quality of Newton should be emphasized. Let me quote from "The History of Physics" by Max von Laue. "It happens more than often that somebody expresses obscure apprehensions and then another investigator comes and brings them to a perfect clarity. Someone makes an observation or comes upon an idea, whose importance is afterwards realized by another. Still a discovery should be dated from the time, when it was formulated with clarity and certainty *sufficient to influence further development*" (italics mine).

Imagine we are Newtons. It is interesting to see, what arguments might lead Newton to his law of gravitation. The question to start with is: how the motion of the planets can be explained? First and foremost, one should know the reason of this motion. For Newton, this was the *interaction* between physical bodies, expressed in their attraction. But this is not all there is to it. One should find the main features of this interaction or, in other words, to establish the law of gravitation. As young as 23, Newton arrived at the conclusion that the motion of the planets was governed by a radial attractive force directed to the Sun and inversely proportional to the square of the distance between the Sun and a planet. But can this assumption be verified? Newton considered that the force exerted on the Moon by the Earth was of exactly the same origin and performed the following simple calculation. To the first approximation, the Moon's orbit around the Earth may be considered as circular. Its centripetal acceleration a may be found from the equation

$$a = r\omega^2,$$

r being the radius of the orbit and ω—the Moon's angular acceleration. The value of r is 60 times the radius of the Earth ($R_E = 6370$ km). As to ω, it can be obtained from the period of the Moon's revolution around the Earth, which is 27.3 days:

$$\omega = (2\pi/27.3) \text{ radian/day}.$$

The acceleration a is then

$$a = r\omega^2 = 60 \times 6370 \times 10^5 \left(\frac{2\times3.14}{27.3\times86\,400}\right)^2 \text{cm/s}^2$$
$$= 0.27 \text{ cm/s}^2.$$

But if the inverse-square-law holds for the gravitational forces, then on the Moon's orbit the Earth-related free-fall acceleration g_M should be

$$g_M = g_0/(60)^2 = (980/3600) \text{ cm/s}^2 = 0.27 \text{ cm/s}^2.$$

We thus have come to the equation

$$a = g_M,$$

that is, the force keeping the Moon in its orbit is identical to that drawing it to the Earth. Another conclusion to be drawn from this result is that the variation of the force with distance has been guessed correctly. With this in mind, Newton was now in a position to write the law of gravitation:

$$F = G\frac{M_1 M_2}{r^2}, \tag{1}$$

where F is the force of mutual attraction between masses M_1 and M_2 separated by a distance r.

The first constant comes to life. So far, the coefficient G is nothing more than a *gravitational constant*. Indeed, there is nothing we can say about it. What is its value? How (if at all) does it depend on the properties of interacting bodies? Or on the temperature? The newly-born constant is wrapped in mystery.

But, leaving it alone for a while, let us see how it happened that the law of gravitation turned upside down the world outlook of the mankind. Note that this law was formulated by Newton together with the laws of dynamics (i.e., laws of motion), and this combination enabled the scientists to calculate theoretically the orbits of the planets. The results of the calculations agreed with long-term astronomical observations, presenting thereby an excellent prove of Newton's laws.

As the first example, let us look how one of Kepler's laws can be derived from those of Newton. The attractive force which the Sun exerts on a planet is

$$F_1 = G\frac{M_{\mathrm{S}} M_{\mathrm{pl}}}{r_1^2},$$

where M_{pl} is the mass of the planet and r_1—the distance from the Sun to the planet (we again approximate the orbit to be circular). The centripetal acceleration of the planet, a_1, is

$$a_1 = r_1\omega_1^2 = r_1\left(\frac{2\pi}{T_1}\right)^2$$

According to the second law of Newton,

$$a_1 = \frac{F_1}{M_{\text{pl}}} = G\frac{M_{\text{S}}}{r_1^2},$$

so that

$$r_1\left(\frac{2\pi}{T_1}\right)^2 = G\frac{M_{\text{S}}}{r_1^2},$$

or

$$\frac{4\pi^2}{T_1^2} = G\frac{M_{\text{S}}}{r_1^3}.$$

For another planet, quite similarly:

$$\frac{4\pi^2}{T_2^2} = G\frac{M_{\text{S}}}{r_2^3}.$$

By dividing the latter equation by the former, we obtain

$$\frac{T_1^2}{T_2^2} = \frac{r_1^3}{r_2^3}.$$

But this is nothing less than the third of Kepler's laws! Formulated half a century earlier, Kepler's laws came first to support Newton's law of gravitation—and in a most brilliant way, too.

But we have stressed earlier, when speaking of good theories, that to explain old facts is not their only aim. The other is to predict new ones. In 1682 a bright comet appeared in the Earth's skies. It came and went and was bound to come back, and Edmund Halley, the eminent English astronomer, used Newton's formulae to calculate the time of its return. The celestial guest was back exactly when predicted, bringing with it another excellent confirmation of the theory.

The discovery of a new planet showed in the most convincing way the power of Newton's law of gravitation. The fact was, that for the planet Uranus, there was no agreement between observations and calculations. Sometimes the planet moved slower and sometimes faster than it should. To explain this phenomenon, A. J. Lexell (1740-1784) of St. Petersburg suggested the existence of a new, still unknown transuranic planet. In 1846, the French astronomer Urbain Le Verrier calculated the motion of this new planet and sent the results to his German colleague Johann Galle. The new planet, later to be called Neptune, was found by Galle precisely where calculated. Fantastic, isn't it, that just sitting at their tables and writing their formulae, scientists should be able to discover a new planet!

It was before long that a new confirmation came for the law of gravitation—this time from far beyond the Solar system. In 1842, Friedrich Bessel of Germany observed periodical deviations of Sirius from its central position. Sirius is a bright star at about 10 light years from us (light year is actually a distance, the one that light travels in a year). The calculations Bessel performed led him to the conclusion that these deviations are due to an invisible satellite. It was indeed found 20 years later.

To say that the discovery of the law of gravitation produced a great impression, is to say nothing. It was impossible now to argue that the motion of the planets was ruled entirely by

God's will. Newton's discovery established the real cause of the motion, throwing overboard all astrological hubble-bubble. Science grew up into a huge power, never again to be looked down!

GRAVITATIONAL CONSTANT

For all its obvious successes, for a long time Newton's theory of gravitation was not able to win a complete recognition. The value of G, the gravitational constant in Newton's formula, remained unknown. Of no avail were the attempts to detect gravitational attraction between bodies in terrestrial conditions. For some scientists, the only solution imaginable was to limit the validity of the law. It was good, they argued, only to describe the motions of heavenly bodies—of planets and stars.

But one might as well ask another question: why is it that the effect of gravitational attraction eludes observation in earth-bound laboratories? What experiment could we set up to hunt it down?

Well, let us estimate the forces we are going to measure. We take two balls each having a mass M_b of 50 kg and place them at a distance $r = 10$ cm from each other. According to Newton's law (1), the force with which they attract each other is

$$F = G\left(\frac{M_b}{r}\right)^2.$$

Without the value of the gravitational constant G, we cannot calculate F. What we can do, however, is to estimate the value of G by using the well-known figure for the free-fall acceleration,

$g_0 = 9.8$ m/s². Indeed, what makes a ball go down to the ground is just the attractive force produced by the Earth:

$$F' = G\frac{M_b M_E}{R_E^2}.$$

According to the second law of dynamics, this force will impart to the ball an acceleration equal to that of free fall:

$$g_0 = \frac{F'}{M_b} = G\frac{M_E}{R_E^2}.$$

Substituting the Earth's mass and radius, we can then calculate the value of the gravitational constant:

$$G = \frac{g_0 R_E^2}{M_E} = \frac{9.8 \times (6370 \times 10^3)^2}{6 \times 10^{24}} \text{ m}^3/(\text{s}^2 \cdot \text{kg})$$
$$= 6.6 \times 10^{-11} \text{ m}^3/(\text{s}^2 \cdot \text{kg}).$$

The force of the mutual attraction between the balls is

$$F = 6.6 \times 10^{-11} \frac{\text{m}^3}{\text{s}^2 \cdot \text{kg}} \left(\frac{50 \text{ kg}}{0.1 \text{ m}}\right)^2 = 1.6 \times 10^{-5} \text{ N}.$$

Let us compare it with the force exerted on the balls by the Earth:

$$F' = 4.9 \times 10^2 \text{ N}.$$

These simple calculations show that the force F' is about thirty million times (!) as large as the force of mutual attraction F. This fully explains the failures to detect the attraction in terrestrial conditions—the observation of such tiny forces on the background of such formidable ones surely requires extremely sensitive apparatus and quite a bit of experimentation skill!

How it was done. In the following narration, we shall often have a chance to see that, surprisingly or not, experimental methods of measurement and their results obtained in apparently different branches of physics are closely interconnected. In our particular case, the help came from electrostatics. In 1784, Charles Coulomb of France invented an extremely sensitive instrument known as the torsion balance. By using it, he discovered the law of interaction of electric charges that bears his name. The same instrument was employed in 1798 by English physicist Henry Cavendish, this time to detect the attraction between small bodies in terrestrial conditions. The way the experiment was set up is shown in Fig. 2. First, two small lead balls 730 g each were suspended at the ends of a beam and then two large 158 kg balls were placed close to them. This was the first time that the gravitational attraction of material objects was observed exper-

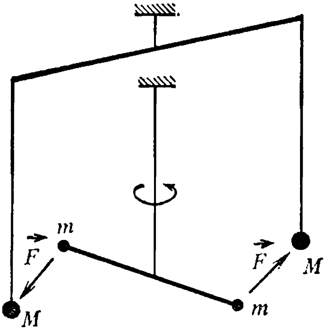


Fig. 2

imentally. As to the value of the gravitational constant, it was measured to be

$$G = (6.6 \pm 0.041) \times 10^{-11} \ \mathrm{m^3/(s^2 \cdot kg)},$$

in full agreement with the estimate above.

The Cavendish experiment is of extreme importance for physics. First, the value of the gravitational constant was measured. Second, the universal nature of the law of gravitation was demonstrated. From that time on it was a universal law indeed.

"THERE IS NOT A SUFFICIENT NUMBER OF EXPERIMENTS"

When studying a physical phenomenon, a physicist is faced with two problems. On the one hand, he has to understand the reason of the phenomenon, on the other—to establish some laws allowing its mathematical description. With the discovery of the law of gravitation, the core of the problem remained unresolved—the equations and formulae could not explain the nature and mechanism of gravitation. The great scientist was fully aware of this: "But hitherto I have not been able to discover the cause of these properties of gravity from phaenomena, and I frame no hypotheses; for whatever is not deduced from the phaenomena is to be called an hypothesis, and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy... And to us it is enough that gravity does really exist, and act according to the laws which we have explained, and abundantly, serves to account for all the motions of the celestial bodies..."

First to answer the "how's" and then the "why's"—this approach is used very often in science. Let me remind you the discovery of the Periodic Table by Dmitriy Mendeleev, the great Russian chemist. It was the keen insight of genius that enabled him to find law and order in apparently disordered multitude of chemical elements. In full accordance with Mendeleev's predictions, a number of previously unknown elements were found. But it took the scientists many years to gain clear understanding of what physics was actually behind the discovery. In more recent times, elementary particle physics gave another example of this kind (see the Sixth Story).

A possible reason or mechanism of gravitation occupied Newton's mind for years. The gravitational force acts through hundreds of millions kilometers of what appears to be absolutely empty space. Newton's intuition revolted at the idea. "That one body may act upon another at a distance through a vacuum, without the meditation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity that I believe no man who has in philosophical matters a competent faculty of thinking can ever fall into it".

The hypothesis of ether. In his efforts to solve the problem, Newton suggests the existence of ether, a special transmission medium for gravitation. But there was nothing definite he could say about its properties: "There is not a sufficient number of the experiments needed to determine and demonstrate accurately the laws governing the actions of this spirit." (Here "spirit" is another word for "ether".)

Was not the ether just an "occult" quality Newton himself had warned against? And yet Newton sought—unsuccessfully—to explain gravitation by the properties of the ether. In 1675 he develops an idea of streams of ether towards the center of the Earth: the streams drag things along with them, which in fact means attraction. In 1679 he proposes that ether's density varies from point to point. The farther from the Earth, the denser the ether, which provides a kind of pressure to push things into the lower-density layers—that is again down to earth. Still, in 1706 Newton dismissed the very idea of the ether. An example of extreme scientific self-discipline may be seen in the fact that in his famous *The Mathematical Principles of Natural Philosophy*, where the law of gravitation is formulated, not a single word is mentioned about its "etherial" mechanisms.

"There is not a sufficient number of experiments"—these are the words Newton left as a guiding rule to his scientific posterity, for generations to come.

Still, the mechanism of gravitation remained an intriguing problem. The great Russian scientist Mikhail Lomonosov believed all space to be filled with some "gravitational matter", whose interaction with bodies should somehow explain their mutual attraction. In 1782, G.L. Lesage of Switzerland advanced an idea that all the Universe was filled with numberless very small and very fast "universal" particles. They move about chaotically in all directions and, when colliding with bodies, transfer to them their motion.

A motionless body suspended in space receives equal number of blows from all sides—and just for this reason remains at rest. The Sun is something like a shield for "universal" particles, so that from this "sunny" side the Earth is less affected by them.That is why the Earth is attracted by the Sun—as well as the other planets. All this sounds fine but—the Earth is moving and the blows of the particles should slow it down, until it comes to a complete halt. Thanks God, nothing like that happens in real life and hypothesis of Lesage was therefore rejected.

But, one may ask, why should we bother so much about the mechanism of gravitation? Whatever mechanism, the law of gravitation works well enough, doesn't it? Well, so it does, but note that this law is a generalization of experimental data and as such is unprovable. It was obtained by the induction method, which means that if a fact has been established and turns out to be true on other occasions, we conclude that it will hold in all similar situations as well. However, until the mechanism of the phenomenon is found, one can never be sure the law is hundred percent true.

With the high sensitivity of the torsion balance, why should we not try to find out the dependence of G on the properties of medium or on the nature of gravitating objects? To see, whether the gravitational forces can be screened or affected in some other way?

Well, all attempts of this kind resulted in nothing. The gravitational constant showed no dependence on physical or chemical properties of the objects studied (indeed, when weighing strawberries we never hesitate to counterbalance them with metallic weights). J. Poynting of Britain failed to detect any effect of temperature on the weight of physical bodies. The experiments on screening also gave nothing. E. Majorana of Italy seems to be the only scientist who claims to have observed such a screening (produced by thick layers of mercury), but so far his result has not been confirmed. Measurements of the gravitational constant are still going on. In 1942, P. Heyl and P. Chrzanowski, by modifying the method of Cavendish, raised the accuracy of the constant up to

$$G = (6.673 \pm 0.003) \times 10^{-11}\ \mathrm{m}^3/(\mathrm{s}^2\cdot\mathrm{kg}).$$

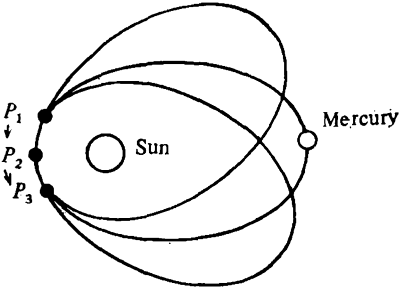
In 1974-1975, M.U. Sagitov of the USSR goes still further:

$$G = (6.6742 \pm 0{,}0031) \times 10^{-11}\ \mathrm{m}^3/(\mathrm{s}^2\cdot\mathrm{kg}).$$

In their search for the mechanism of gravitation, scientists used eclipses to study the attraction of the Earth by the Sun. In one of such experiments, M. Allais of France noted some unusual features in the motion of a clock pendulum. The experiment was repeated by Soviet scientists in 1961, when an eclipse went across a large part of the USSR, but without any conclusive result. The force of gravity seemed indeed to vary somewhat, but this might well be explained by some irrelevant effects. Gravitation stubbornly kept its secrets!

Experiment contradicts Newton's theory. The nature of gravitation became still more a thing in itself, when a fact was established, incompatible with Newton's theory. Le Verrier points out in 1845 that the perihelion (the nearest to the Sun point of the orbit) of Mercury displaces by

43 angular seconds per century (see Fig. 3). This is, of course, a very small amount, but the point is that, according to Newton, no such motion should occur at all. One might save the day by assuming that force of gravitation decreases with distance as $r^{-2.00000016}$ rather than r^{-2}. But the inverse-square-law had been found to be correct on so many other occasions! Also of no use was Laplace's hypothesis that gravitation is "absorbed" in the interplanetary space according to the formula



Actual orbit
(strongly magnified)

Fig. 3

$$F = G\left(\frac{M_1 M_2}{r^2}\right) e^{-\lambda r},$$

where e is the base of natural logarithms ($e = 2.718...$). (From the actual value of the perihelion's displacement, the coefficient λ should be 0.00000038.) Note that Mercury is nearest to the Sun in the Solar system (see Fig. 1) which means that it moves in a stronger gravitational field than any other planet.

From the point of view of the evolution of science, two major conclusions are to be drawn from the fact of the perihelion's displacement. First, any theory is tested by observations and therefore one and alone observation may suffice to upset a theory—if the theory fails to explain it. In our particular case, the behavior of the planet throws doubt upon Newton's claim that his theory explains "all the motions of the celestial bodies". In this sense, Mercury disproved Newton's theory. And another conclusion: our knowledge is of only relative nature and we should therefore be more active in our search for the Truth.

Well, so much for the gravitational constant. What have we learnt about it? Two centuries after the discovery of Newton's law were the most fruitful period for the problem of gravitation and the "number of experiments" was increasing steadily. Still the observation of astronomical objects failed to reveal the secrets of the phenomenon. It was from the world of atoms and electrons that new fundamental ideas were to come—to initiate further progress and, in fact, to provide a basis for Einstein's theory of gravitation. It is therefore the demand of logic—of science and of the book—that we turn now to molecular and atomic physics, with constants of their own.

SECOND STORY

Lives of Hardship or the Tale of Avogadro's and Boltzmann's Constants

TRUTH FORESEEN

In 1908, Jean Perrin suggested that the number of molecules in a mole of any substance should be called the constant of Avogadro-Ampére. It was about hundred years after Avogadro had advanced his fundamental hypothesis, and 52 years after his death. And it was not until even later that, in accordance with historical justice, this universal constant came to be known as Avogadro's number. The work of the scientist was at last duly appreciated. But why so late?

The story of Avogadro's number is in fact the story of our views on the structure of substance, so that a short historical survey of the subject seems to be relevant here. We shall then be prepared to better understand the constants' role in physics.

The structure of the world intrigued the man from the earliest times and it was at the dawn of civilization that two major approaches to the problem were formulated. According to one of them, there existed some primary element of which all substances were composed. For the ancient Greek philosopher Hesiod, it was earth. Thales of Miletos taught the primary element to be water, Anaximenes believed it was air, Heraclitos—fire. Empedocles admitted that all the four might exist simultaneously. Plato thought that under certain conditions one primary element could change into another. For Aristotle, there was only one primary element, called substrate, which never remained alone but combined with a pair of qualities to produce the "conventional" elements:

substrate + warmth + dryness = fire,
substrate + warmth + dampness = air,
substrate + cold + dampness = water,
substrate + cold + dryness = earth.

Surely enough, these views did not gain a support of practice. What all these thinkers had in common was that, for all of them, substance was not composed of individual particles but was considered instead as a continuous solid and uniform mass. In this approach, there was in fact no problem of the inner structure of substance. That one element may sometimes change into another, is, perhaps, the only valuable idea to be found in these old teachings.

The chief exponents of the second—essentially different—approach were Leucippos, Democritos and Epicuros. In their view, substance was composed of tiny indivisible and impenetrable particiles of various sizes and forms. These particles they called *atoms* (originating from the Greek word "a-tomos", meaning indivisible). "These atoms, which are separated from each other in the infinite void and distinguished from each other in shape, size, position and arrangement, move in the void, overtake each other and collide. Some of them rebound in random directions, while others interlock because of the symmetry of their shapes, sizes, positions and arrangements, and remain together. This was how compound bodies were begun". This is a structure of matter as seen by Democritos. These ideas were, of course, much closer to our modern views, but still no experiment could confirm them at the time. On the part of ancient philosophers, this was an ever-to-be-admired act of pure intuition.

The idea of one element changing into another was caught up by medieval alchemists. The miracle-working "philosophical" stone capable to convert things into gold—that was their dream that took away a great deal of effort and time. But dream it remained, for there was nothing truly scientific in it. The beginning of true science—as far as the structure of matter is concerned—should be dated from the second half of the seventeenth century. It was then that quantitative methods of investigation were first introduced into physics and chemistry.

The first corpuscular theory to explain the structure of matter from atomistic point of view was developed by the English scientist Robert Boyle (1627-1691). Mikhail Lomonosov (1711-1765) held similar views on the structure of substance. In his words, "The corpuscle is a combination of elements; the element is a part of a body, not composed of any other, smaller and different bodies". (In later terminology, "element" should be understood as atom and "corpuscle" as molecule.)

The French scientist Antoine Lavoisier (1743-1794) put forward the first classification of chemical elements. It was far from being irreproachable: light and phlogiston, for example, were included into the list of primary elements, along with oxygen and nitrogen. But certainly these mistakes are excusable: at the time the very existence of the atom had not yet been proved and atomism was making its first hesitating steps.

The next important figure in this story was the English chemist John Dalton (1766-1844). His work was highly appreciated later by the great Russian chemist D.I. Mendeleev. "Thanks to the genius of Lavoisier and Dalton", he wrote, "mankind found in the invisible world of chemical combinations simple laws of the same nature that had been pointed out by Copernicus and Kepler in the visible world of planets". For the first time in the history of science Dalton suggested a clearcut definition of the atomic weight of an element. This was the ratio of the mass of one atom of this element to the mass of one atom of hydrogen. In 1803, Dalton discovered the law of multiple proportions, according to which elements may only combine with one another in proportions 1 : 1, 1 : 2, etc. This was the starting point for his table of relative atomic masses of elements, the first such table in chemistry. (Relative molecular (atomic) mass of a substance is the ratio of the mass of its molecule (atom) to 1/12 of the mass of a carbon atom.) This table was unsatisfactory in many ways. Among other things, Dalton considered all gases to be monatomic, a mistake that led him to incorrect chemical formulae for a number of compounds—OH for water, for example. However, Dalton's achievements in the atomic theory of chemistry made him a figure of high esteem in the eyes of his contemporaries.

Paradoxically, Dalton never accepted the Law of Combining Volumes, discovered in 1808 by the French chemist J.L. Gay-Lussac. The law states that if gases interact and form a gaseous product, the volumes of the reacting gases and the volumes of the products are in simple proportion. To give an example, two volumes of hydrogen combine with one volume of oxygen to produce two volumes of water vapour. The law disagreed with Dalton's atomistic theory in which equal quantities should combine. Rather a dramatic situation emerged: Gay-Lussac himself did not attach any theoretical significance to his law, Dalton refused to accept it, while the law itself had been established beyond any doubt and discredited the whole of the atomistic theory.

A brilliant solution of the crisis was pointed out in 1810 by Amedeo Avogadro, professor of mathematics and physics at Vercelli, Italy. He managed to unite Dalton's atomistic theory and the law of Gay-Lussac by stating that quantitative ratios of substances in compounds only depend on the relative number of atoms comprising the compound and on the number of molecules they form. Therefore he assumed that there are also some simple relations between the volumes of gaseous substances and the number of molecules they are composed of. He came to the most natural and apparently the only reasonable hypothesis that the *number of molecules is always the same in equal volumes of all gases or it is always proportional to the volumes* (italics mine). Thus, for the first time, Avogadro introduced into science the notion of the molecule as a combination of atoms. This provided an immediate explanation for the law of Gay-Lussac: two volumes of molecules of hydrogen in combination with one volume of molecules of oxygen produce two volumes of molecules of water vapour:

$$2H_2 + O_2 = 2H_2O.$$

Thus disagreeing with Dalton in that all gases are monatomic, Avogadro was brave enough to oppose the most undisputable authority in the atomic theory!

One consequence of Avogadro's hypothesis was that the ratio of the volumes of reacting gases could be used to determine the composition and relative molecular masses of chemical compounds. The table compiled by Avogadro was much more correct than that of Dalton.

Avogadro's number. An implication of Avogadro's hypothesis—the one, indeed, that makes it so extremely significant—is that a mole * of any substance contains a constant number of molecules. If M is a molar mass (the mass of one mole of a substance) and m is a relative molecular mass, then, quite obviously,

$$M = N_A m,$$

where N_A is the number of molecules in a mole. It is the same for all substances:

$$N_A = \frac{M}{m}.$$

---

* A mole is the quantity of a chemical substance that has a weight in mass units (as grams) numerically equal to the molecular weight or that in the case of a gas has a volume occupied by such a weight under specified conditions (as 22.4 liters at 0 °C and a pressure of 780 milliliters mercury).

With this understanding another important result can be obtained. Avogadro's hypothesis tells us that the same number of gas molecules always occupies the same volume. It then follows that the volume V_0 of a mole of any gas at normal conditions is a constant quantity (normal conditions are taken to be 0°C and one atmosphere (1.013×10^5 Pa) of pressure.) This molar volume was soon afterwards measured and turned out to be

$$V_0 = 22.41 \times 10^{-3}\ \text{m}^3.$$

The determination of N_A, the number of molecules in a mole of any substance (later to be called Avogadro's number), became an urgent problem of science. In the third section of this chapter we shall get familiar with the methods used for the purpose. For the moment, however, let us consider the value of N_A to be known:

$$N_A = 6.022 \times 10^{23} \quad \text{molecules/mole}.$$

As the following simple calculations show, the knowledge of V_0 and N_A helps to get the most important characteristics of atoms and molecules.

Since the mass of one mole of hydrogen H_2 is 2.016 g and the mole contains N_A molecules, the mass of one molecule of hydrogen is

$$m_{H_2} = M/N_A = 3.35 \times 10^{-24}\ \text{g}$$

and the mass of a hydrogen atom is

$$m_H = 1.675 \times 10^{-24}\ \text{g}.$$

We have thus managed to "weigh" a hydrogen atom without using a balance (and no balance, I'm afraid, is accurate enough for the purpose).

We shall now estimate the dimensions of atoms and molecules. Let us take one cubic centimeter of water. This is 1/18 of the mole of water, so that it contains $(6.022 \times 10^{23})/18 = 3.34 \times 10^{22}$ water molecules. One such molecule occupies the volume $1/(3.34 \times 10^{22})$ which is aproximately 3×10^{-23} cm^3. Assuming that the molecules in liquid are closely packed, we estimate the linear dimension r of a water molecule:

$$r = \sqrt[3]{3 \times 10^{-23}} \text{ cm} \approx 3 \times 10^{-8} \text{ cm}$$

(which is, by the way, the right order of magnitude for other atoms and simplest molecules).

Another question of interest is how far apart the molecules of a gas are. In one mole, the molecules themselves occupy the volume V_M which is

$$V_M = \frac{4}{3} \pi r^3 N_A \approx 70 \text{ cm}^3.$$

The ratio of V_M to V_0 is about 3.2×10^{-3}, that is the volume of the molecules is only a very small fraction of V_0. We can now estimate V_1, the volume per molecule:

$$V_1 = \frac{V_0}{N_A} = 3.7 \times 10^{-20} \text{ cm}^3$$

and the average distance r_1 between the molecules:

$$r_1 = \sqrt[3]{V_1} \approx 3.5 \times 10^{-7} \text{ cm}.$$

Gas molecules are thus separated by distances about ten times as large as their dimensions! To sum up, Avogadro's number enabled us to calculate easily the size of atoms, their mass and average separation and to form thereby a visible picture of invisible world. Isn't it a wonderful number!

One important implication of Avogadro's hypothesis cannot be overemphasized. Following the pioneering work of Boyle and Dalton, it brushes aside the old idea of continuity of substance and introduces into science the concept of grainy, granular or *discrete* structure of matter. The full significance of this novel concept will be understood by the reader in the following Stories of the book. For the moment, let us point out that while in Avogadro's days the atomic structure of substance was no more than a conjecture, modern physics has provided direct evidence for the existence of atoms and molecules. Avogadro's hypothesis is not a hypothesis any longer—it may well be called Avogadro's law!

In his lifetime, however, Avogadro's work was all but ignored by scientific community. The reason was, perhaps, that Avogadro was not a chemist-experimenter and was not able therefore to prove his ideas experimentally. At his time, as Planck pointed out, Avogadro was the only theoretician among physicists. But the most damaging for his recognition by contemporaries was a very similar hypothesis advanced three years later by the famous French physicist A. Ampére. At the time, the French school of physics was of extreme influence and its achievements were undisputable. Italy, on the contrary, was then a province of science and no wonder that neither Ampére nor his followers were in any hurry to acknowledge the priority of an Italian scientist. The more so that numerous short-lived hypotheses were emerging one after another to add to the confusion and uncertainty of the young atomic theory, with the very existence of the atom still open to question. It was at the First International Chemical Conference as late as 1860, four years after Avogadro's death, that his priority and his scientific merits were fully recognized.

THE ARCHITECT OF HARMONY

In the preceding section, we got familiar with the basic ideas of the atomic picture of matter—of gases in particular. Now the question is to be asked: how are we supposed to describe these huge systems of particles? Note that one cubic centimeter of gas contains at normal conditions as many as

$$N_{\mathrm{L}} = \frac{N_{\mathrm{A}}}{V_0} = 2.687 \times 10^{19} \text{ molecules.}$$

(This constant is called Loschmidt's number, after an Austrian scientist J. Loschmidt.) Do we have any hope of describing them by the methods of Newtonian mechanics?

To trace the motion of every single molecule, we would have to solve simultaneously as many as about 10^{20} equations, an impossible task for even the largest computers available. The calculation of molecules' trajectories is therefore doomed from the very start. To find the laws governing the behavior of gases, a new theoretical approach is needed.

Molecular-kinetic ideas. What makes the description of gases still more complicated problem is that gas molecules are in permanent chaotic motion. (This is the reason why the odour of lilies placed on the window-sill is soon felt all over the room.) However, the distance between the particles being pretty large, for most of time they do not interact with each other just travelling in straight lines. When colliding they exchange their energy and change the direction of their motion—much in the same way as billiard balls do. It is quite obvious that in equilibrium the velocities of molecules should be distributed uniformly over all spatial directions (Fig. 4) (otherwise the flux of gas would appear).

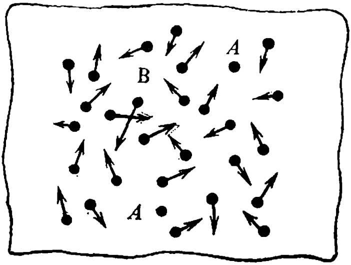


Fig. 4

If we try to include the collisions of molecules, the 10^{20} equations that we have already refused to deal with would become still more complicated: the collisions would make all of them interdependent!

Such were what might be called objective difficulties. But to make things worse, subjective—or psychological—difficulties were also there. By far too small were the objects to be studied: about 10^{-8} cm in diameter, with a mass of only about 10^{-24} g. It seemed incredible that the reality of these puny things could ever be proved. It is this scepticism that gave birth to the so-called "descriptive" physics. It is impossible in principle, its followers taught, to comprehend the essence of phenomena and the aim of physics should be reduced therefore to a pure description of phenomena and regularities. All the attempts to reveal inner mechanisms of phenomena were denounced as nonscientific. The German philosopher and physicist Ernst Mach went still further. In his view, there was no physical reality at all and all the phenomena we perceive were only due to our subjective sensations.

Fortunately, these pessimistic views were opposed by people who firmly believed in the reality of atoms. Of these, the leading figure was, of course, Ludwig Boltzmann (1844-1906), the great Austrian theoretical physicist, whose name is linked with fundamental works in quite a number of fields. "This is only a hypothesis, of course," he wrote, "that such extremely small bodies (atoms) do really exist and their combined action produces the bodies perceived by the organs of sense. Some time, maybe, the atomistic hypothesis will be replaced by some other hypothesis but it is extremely unlikely". Boltzmann was strongly convinced of the power inherited in the human mind to comprehend the essence of phenomena. He objected to Mach: "What we have to do is not to deduce natural phenomena from our notions but, on the contrary, to adjust these latter to natural phenomena".

In Boltzmann's time, his novel concepts of matter were often denigrated or at least ignored. Today, his kinetic theory is a matter of everyday work of a physicist. Let us take now a look at the basic ideas that it contains.

Do we need the paths of molecules? It is a well-known fact that a gas spreads out to fill, fully and uniformly, all the volume available. It is improbable that the density of a gas should be different in various parts of the volume. We cannot imagine, indeed, a ball with one side slack and another resilient and well-pumped. Squeezing a ball, we always feel it tough and equally pumped on all its sides. This simple fact implies that the properties of a gas, when in equilibrium, are fully independent of the initial positions of its molecules. But then the knowledge of the molecules' paths is completely devaluated! The motions of individual molecules are of no significance in determining the equilibrium properties of a gas. With the number of the particles being so fantastically large, what matters is their behavior *on the average.*

Let us take a ball again. We know very well that its round shape results from the pressure the gas exerts on its walls. But what does it mean—the pressure of a gas? The kinetic theory explains it as follows.

As a result of their continuous motion, the molecules will collide now and then with the walls of the ball. In doing so, they push against the walls and go back into the inner part of the volume. In every such reflection, the normal-to-the-surface component of the molecule's velocity will reverse its direction. This gives rise to the force acting on the inside surface of the ball. It is this force that we call the pressure of a gas. Since the number of particles is large, it follows that various sections of the ball's surface will receive, on the average, equal number of blows by the molecules. Thus, the pressure of a gas is, in fact, an average quantity resulting from the collisions of a large number of molecules with the wall. At any moment, of course, the true (instantaneous) pressure of a gas may differ somewhat from the average one, so that in the long run we obtain something like a saw-tooth picture, as shown in Fig. 5. There is little to worry about, however. It can be shown (and this is a result of statistical treatment) that, in measuring a pressure, the error due to these "fluctuations" is of the order of $N_A^{-1/2}$, or typically 10^{-12} percent. For all practical purposes, such an error may be ignored and the measured pressure considered as the true one.

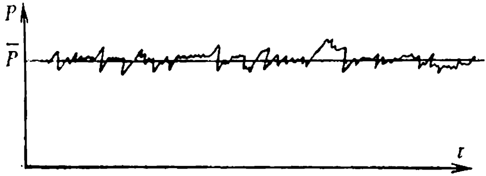


Fig. 5

The laws of gases. These laws provide an excellent illustration to what we have just said. Certainly, everyone is familiar with them—but let me remind them here, just in case. The first of them, the law of Boyle and Marriotte, relates the pressure p of a gas to its volume V at a constant temperature:

$$pV = \text{const.}$$

The law of Gay-Lussac describes the change in the volume of a gas caused by the change in the temperature:

$$V = V_0 \, \alpha T,$$

where α is the thermal expansion factor for gases, (1/273) K^{-1}. Let us combine these two equations. We then come to the equation of state for an ideal gas in which all the three parameters of gas are linked together:

$$\frac{pV}{T} = R = \text{const.}$$

The quantity R in this equation is known as the universal gas constant. To get its value, let us remember that at normal conditions ($p = 1.013 \times 10^5$ Pa and $T = 273$ K) one mole of a gas occupies the volume $V_0 = 22.41 \times \times 10^{-3}$ m^3. We then find:

$$R = \frac{pV_0}{T} = 8.31 \text{ J/mole} \cdot \text{K}.$$

The universal gas constant is in fact the amount of energy acquired (or lost) by the molecules of a mole of gas if its temperature is varied by one degree.

It should be emphasized here that the laws of gases are valid for all gases without any exception, no matter what their chemical composition. From what we have just learnt, this is quite understandable. Indeed, oxygen, nitrogen or air are just the systems made up of large numbers of weakly interacting particles and the average characteristics of such systems are insensitive to the nature of the particles.

Calculation of average values. With the coming of the kinetic theory, the computation of average values becomes the most important problem. And extremely difficult, too: indeed, we have to take an average over a tremendous number of particles $\sim 10^{20}$. Where are we going to start from?

When the molecules of a gas collide with one another, they exchange energy. After the collisions some of them acquire an additional kinetic energy and move faster, the others lose their energy and are slowed down. In other words, we have some distribution of speeds of the molecules in a gas. Let us assume that this distribution is given by the curve shown in Fig. 6. The average speed of gas molecules may then be calculated as follows.

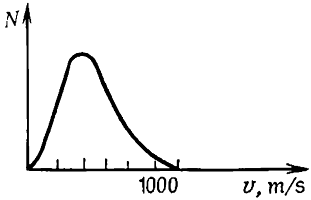


Fig 6

Let us divide the area under the curve in the way shown in Fig. 7, where the lengths along the axis of speeds are all equal. We may assume, for the sake of simplicity, that all the particles whose velocities fall into such a length are characterized by one average velocity, namely by that corresponding to the middle of the length (obviously, the shorter the lengths, the better the approximation). The average velocity of the gas molecules is then defined as

$$\bar{v}=\frac{N_1v_1+N_2v_2+\ldots+N_nv_n}{N_1+N_2+\ldots+N_n},$$

where an index specifies a "rectangle", while v_i and N_i are, respectively, the corresponding speed and the number of the particles (the sum $N_1 +$

$+ N_2 + \ldots + N_n$ is the total number of the particles). Note, however, that in order to actually perform such a computation, we need to know the function $N(v)$ or the *velocity distribution of gas particles.*

In the middle of the nineteenth century, the remarkable Scottish physicist James Clerk Maxwell (1831-1879) derived (or rather "guessed" as Max von Laue put it) the first function of this kind. But it was Ludwig Boltzmann who not only went further in this particular direction but was also able to formulate and solve a number of central problems of the newborn kinetic theory.

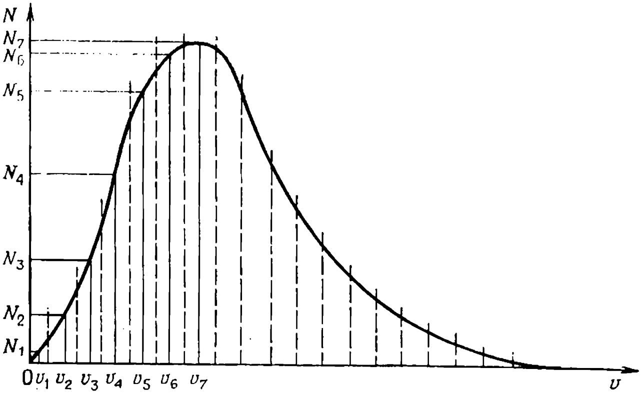


Fig. 7

Boltzmann's fundamental results. Maxwell's distribution function was only obtained for monatomic gases. Boltzmann extended this result in more than one way. To begin with, he proved that the same velocity (or energy) distribution of molecules holds for all gases. He then demonstrated that if the rotation and vibration of molecules are taken into consideration essentially the same distribution is valid again. He was able, further, to deduce the energy distribution for molecules affected by external forces (the force of gravity, for example). In this case, the number $n\ (E)$ of the molecules with a given energy E is

$$n\ (E) \sim Ae^{-BE},$$

where A and B are just coefficients (you remember that the energy E of a particle is the sum of its kinetic and potential energies). This relation was used by Boltzmann in deriving his widely-known *barometric* formula which gives the concentration of air molecules as a function of height;

$$n_h = n_0e^{-Ch}.$$

(Here n_0 and n_h are the concentrations of air molecules at the sea level and a height h, respectively; C is a coefficient.) It was with the use of this formula that the French physicist Jean Perrin managed to obtain a direct experimental evidence for the reality of atoms (and to measure Avogadro's number, as the reader will see later in this Story).

Another important result of Boltzmann should be mentioned here. You are familiar, of course, with the notion of degrees of freedom. For a free atom, for example, their number is three, which corresponds to the three coordinate axes: x, y and z. For molecules, the number is increased, since the rotational and vibrational degrees of freedom are added. Boltzmann found that in large systems the energy is equally divided among all the degrees of freedom, the average kinetic energy $\bar{E}$ being proportional to the absolute temperature T:

$$\bar{E} \propto T.$$

Let us take a closer look at this relation. An important thing about it is that a *macroscopic parameter of a gas*—its temperature T—*is a measure of the energy of individual micro-particles* (molecules and atoms). A quite tangible and easy to measure quantity, temperature, gives us an idea of the behavior of unimaginably small and invisible particles! It is certainly a far cry—from disputes about the existence of atoms to the definition of their energies and velocities. The parameters of the microworld become now the objects of investigation.

The bridge between two worlds. Let us try to determine the coefficient omitted in the above relation. To do so, we may apply the fundamental equation of the kinetic theory:

$$p = \frac{2}{3} n\bar{E},$$

where n is the concentration of gas molecules. Let us multiply both sides of this equation by a molar volume V_0. Since nV_0 is the number of molecules in a mole, we find

$$pV_0 = \frac{2}{3} N_A \bar{E}.$$

On the other hand, by the equation of state for an ideal gas

$$pV_0 = RT.$$

Thus,

$$\frac{2}{3} N_A \bar{E} = RT,$$

or

$$\overline{E}=\frac{3}{2}\,\frac{R}{N_{\text{A}}}\,T.$$

The ratio R/N_{A} is a constant quantity, the same for all substances. At the suggestion of Max Planck, this new universal physical constant was named *Boltzmann's constant* and is usually denoted as k:

$$k=\frac{R}{N_{\text{A}}}. \qquad (2)$$

(It may be regarded as the universal gas constant R related to one molecule.) Substituting R and N_{A}, the value of Boltzmann's constant is found to be

$$k=\frac{R}{N_{\text{A}}}=\frac{8.31\ \text{J}\cdot\text{mole}}{6.023\times10^{23}\ \text{K}\cdot\text{mole}}=1.38\times10^{-23}\ \text{J/K}.$$

Using equation (2), we may now write:

$$p=nkT,$$

$$\overline{E}=\frac{3}{2}\,kT.$$

It may well be said that Boltzmann's constant connects the characteristics of the micro-world (the average kinetic energy of particles, $\overline{E}$) with the characteristics of the macro-world (the pressure and temperature of a gas). The latter equation, for example, shows how the average kinetic energy of a micro-particle changes when the temperature of the gas is changed.

The speeds of molecules. With Boltzmann's constant now at our disposal, we can estimate the speeds of gas molecules. The average kinetic energy $\overline{E}$ and the average square of the speed of a molecule $\overline{v^2}$ are well known to be related by

$$\overline{E} = \frac{m\overline{v^2}}{2},$$

so that

$$\overline{v^2} = \frac{2\overline{E}}{m} = \frac{3kT}{m}.$$

For example, for hydrogen molecules ($m_{H_2} = 3.35 \times 10^{-24}$ g) at 0°C (or 273 K) we obtain $v = 1800$ m/s.

The secrets of the invisible world are being revealed, one by one. The knowledge of Avogadro's number has provided us with the dimensions and masses of microparticles. Boltzmann's constant enabled us to get an idea of their energies and speeds.

When first obtained, the above estimates came as rather a surprise for many. If the molecules are this fast, why then the smell of flowers propagates so slowly? The point is that it is only between the collisions that the molecules move in straight lines. When a collision takes place, a molecule changes its direction abruptly. But the number of the collisions is extremely large for each molecule —about a billion per second. The effect of this is that the path of each molecule is extremely entangled and complicated (as you can see in Fig. 8) and the average velocity of a molecule in a particular direction turns out to be quite moderate.

In the days of Boltzmann, the existence of atoms had not yet been proved and the works on the atomistic theory were often ridiculed as the candidates for dusty library shelves. Being well ahead of their time, Boltzmann's ideas met no recognition in his lifetime. The staunch defender of the atomistic views, he worked under continuous attacks of the adherents of "descriptive physics", virtually alone to oppose numerous and well-organized enemies. The significance of Boltzmann's work was appreciated by V.I. Lenin: "... His theory of knowledge is essentially materialistic."

It was only in the end of his life that Boltzmann's revolutionary views began to force their way into the minds of scientists. In 1908—only two years after his death—the brilliant experiments of Jean Perrin proved the reality of atoms, thus presenting the most convincing argument to vindicate Boltzmann's ideas. That one of the most fundamental physical constants bears his name is, of course, an acknowledgement of Boltzmann's immense contribution to physical science.

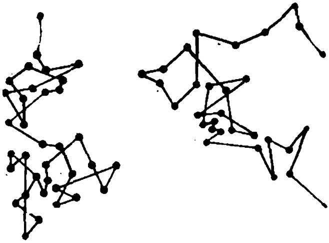


Fig. 8

HOW ARE ATOMS COUNTED?

To find the precise number of molecules in a mole of a substance was one of the most difficult problems faced by experimental physicists in the second half of the nineteenth century. It was necessary to find an appropriate method of measurement, to perform the experiment, to deduce the value of N_A from experimental data and, most difficult of all, to convince sceptics, to make people believe in the existence of atoms and molecules. The *problem of measurement was of principal importance for moving the atomic, discrete structure of matter.*

Nowadays quite a lot of methods have been proposed to measure Avogadro's number—more than 20. The early experiments were only capable to give a rough estimate of the constant, but as the time went on, all the advancements of modern physics were employed to get the more and more precise value of N_A. Let us have a brief look at some of these methods.

One of the first attempts of this kind was undertaken by J. Loschmidt. Considering pressure to be a result of collisions between the molecules of a gas and the walls of the container, he came in 1866 to a correct conclusion that a relationship should exist between the pressure and Avogadro's number. In 1873, Van der Waals showed that N_A should be larger than 10^{23} mole^{-1}. To obtain a more accurate figure, he used the state equation for a real gas which he had earlier derived:

$$\left(p+\frac{a}{V^2}\right)(V_0-b)=RT,$$

where the correction terms b and a take into account, respectively, the finite dimensions of molecules and the increase of the intermolecular interaction at high pressures. This gave $N_A \approx \approx 6.2 \times 10^{23}$ mole^{-1}, a result which was not readily accepted, however, because there were too many assumptions Van der Waals had used in his approach. Even so, his efforts were appreciated—if not admired—by physicists of the time and the revolutionary impact of his work can hardly be denied. For an increasing number of scientists, an exact measurement of this fundamental constant was only a matter of time.

Altogether different approach was suggested in 1871 by the English physicist Lord Rayleigh. He proposed to use the effect of dispersion of light in the atmosphere. When a light beam travels in the air, what makes it visible is in fact its scattering by dust particles. If beams differ in wavelength (color), they are scattered differently. The blue light, for example, having a wavelength of 0.4 micrometer, is scattered more intensely than the red (0.7 micrometer). This is just the reason why the skies are blue (because, for the oncoming sunlight, the molecules of the air are the scatterers of the same kind as the dust particles in the above example).

Lord Rayleigh derived a formula for the ratio of the intensities of incident to scattered light. The formula shows that this ratio increases (as one certainly should expect) if the air becomes more rarified. To prove the formula and to obtain Avogadro's number as accurate as possible, it was, therefore, imperative that the measurements be performed high in mountains—the more so that there are no (atmospheric) dust and water particles there to obscure the results. (Perhaps, it was from that time that mountaineering became so popular with physicists.) The first results were obtained by the English scientist William Thomson (Lord Kelvin). The measurements were carried out on the mountain Monte

Rosa, in Italy. Actually the brightness of the Sun was measured at the zenith and at 40 degrees above the horizon. When comparing these quantities, Thomson was able to find the limits for Avogadro's number:

$$3 \times 10^{23}\ \text{mole}^{-1} \leqslant N_A \leqslant 15 \times 10^{23}\ \text{mole}^{-1}.$$

Later, similar studies were performed by the French physicist L. Brillouin. His result for N_A was 6.0×10^{23} mole^{-1}.

It was the Brownian motion that provided the most convincing evidence for the reality of microparticles and gave the most reliable (for the time) method to determine Avogadro's number. The effect was discovered in 1827 by a Scottish botanist named Robert Brown. He observed (under a microscope) a continuous chaotic motion of very small powder particles suspended in a liquid. The reason of the effect remained a mystery for a long time. The attempts were made to explain it by vibrations of the laboratory table, by some currents moving in the liquid, etc., but none of the explanations survived an experimental test. But it was established for certain that the particles moved faster if they were made smaller and/or if the temperature of the liquid was raised. In 1863 C. Wiener, reviewing the experimental evidence available, concluded that the effect cannot be explained by any forces external to the liquid and should be linked with the thermal motion of the liquid's molecules and their collisions with Brownian particles. This explained immediately the dependence of the Brownian motion on the size of the suspended particles. If a particle is large, the number of the molecules hitting it on different sides is roughly the same, with the result that it remains motionless. For a smaller particle, the random blows coming from various sides fail to balance each other and the particle is therefore in a continuous motion, its speed and direction frequently and abruptly changing (see Fig. 8). The Brownian motion, a visible and well observable experimental phenomenon, was thus explained in terms of invisible and intangible molecules, much adding to the plausibility of the kinetic theory.

From a qualitative description to the theory of the Brownian motion. One of the fundamental works published by Einstein in 1905, was titled "On the Movement of Small Particles Suspended in a Stationary Liquid Demanded by the Molecular Kinetic Theory of Heat". He pointed out in this paper that the Brownian motion can be used to demonstrate the scientific validity of the kinetic theory and atomistic hypothesis. By applying appropriate mathematics to the simple picture we have just discussed, he was able to derive the mean-square displacement $\overline{x^2}$ of a Brownian particle:

$$\overline{x^2} = \frac{RT}{3\pi \eta r N_A} t,$$

where r is the radius of the particle, η—the viscosity of the liquid and t—the time. Apart from N_A, all the quantities on the right are well known, so that by measuring $\overline{x^2}(t)$ we can determine Avogadro's number. By 1908, the great French experimental physicist J. Perrin had tested and confirmed Einstein's formula in what should be regarded as an extremely sophisticated and painstaking experiment. The central technical problem was that of obtaining small (but visible) particles of nearly equal size. Perrin solved it by making emulsions of gamboge that could then be centrifuged to yield the desired particles. By observing the distances that the Brownian particles travelled, he found N_A to be approximately 6.85×10^{23} mole^{-1}. Another important thing about the Perrin experiment was that it confirmed Boltzmann's barometric formula. A drop of emulsion was placed between two horizontal glass plates and the height distribution of the gamboge particles was observed through a microscope. The experiment showed most definitely that the number of the particles decreased with height (see Fig. 9). The microscope was focused onto the individual layers of the emulsion, their photographs were taken and the number of the particles in each layer was then counted. (The examples of such photographs are shown in Fig. 10.) The decrease in the particles' concentration with height was in a perfect quantitative agreement with Boltzmann's formula. The experiments of Perrin were thus a great triumph of the atomistic hypothesis

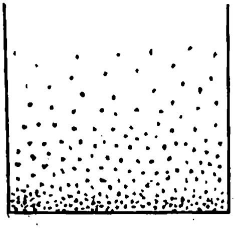


Fig. 9

and from the year 1908 the existence of atoms and molecules could no longer be doubted.

We will not discuss here the other methods to determine Avogadro's number. These include, for example, the use of electrolysis data (see the next Story), the study of the radioactive decay of radium, the measurement of the blackbody radiation. The most precise results come from X-ray scattering on crystalline solids. If the X-rays have wavelength λ and the interatomic separation in the crystal is a, then N_A is given by

$$N_A = \frac{fM}{V_0 \rho_{cr}},$$

where M is the relative molecular mass, ρ_{cr} is the density of the crystal and V_0 is the volume of its elementary cell (which contains f molecules). All of the quantities involved may be determined with an extremely high accuracy, and the method presents therefore the most precise value of Avogadro's number:

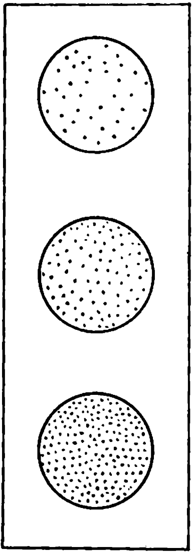


Fig. 10

$$N_A = (6.02205 \pm 0.00016) \times 10^{23} \text{ mole}^{-1}.$$

As the American physicist Millikan once remarked, we know Avogadro's number with by far greater accuracy than the number of inhabitants of New York.

THIRD STORY

Guiding Star or the Tale of the Charge and Mass of the Electron

COMPLETED THEORY OF... UNKNOWN

The variety of natural phenomena is amazing. In our first chapter we discussed gravitation, in the second—the structure of substance. We have not yet said a word about such things as electricity, light or microparticles, and certainly there are a lot of phenomena that we shall not even be able to mention in this short book. With this mass of information and facts, it is easy to lose one's bearings and take a wrong course on the way to Knowledge. But, as a seaman or a traveller are led by the Polar Star in their wanderings, so were physicists at the turn of the century led by the bright guiding star—the Electron.

Indeed, the studies associated, in this way or another, with the electron and its motion, allowed physicists to explain on a common basis dissimilar physical phenomena: electricity and magnetism, light and electromagnetic waves. The study of the electron revealed to the physicist the structure of the atom and led him into the world of elementary particles. Sometimes, the electron provided a thorough understanding of well-known physical facts from entirely new viewpoint. On the other hand, the study of the electron led to discoveries of a large number of new phenomena. These did not find explanation in the framework of old classical physics and new twentieth-century physics came to explain them. So, if the charge and rest mass of the electron look today modest and unconspicuous among their fellow-constants, this does not correspond in the least to the great, indeed revolutionary, role of the discovery of the electron. But for this discovery, we would not be able, in fact, to go any further in our story.

Today, the words "electron" and "electricity" are among the most frequently used. In the evening, millions of electrical lamps drive darkness away. Our everyday life and work are hardly possible without electrical machines and devices of too many types to be enumerated. Every upper-grade schoolboy knows for certain that "the electron is an elementary particle carrying a unit of negative charge". It is hard to imagine the time when somebody could be found completely unaware of the electron. And yet, it was as recently as 1897 that the electron was discovered.

Similarity and otherwise. A very curious and instructive analogy is to be seen between the atomistic theory discussed in the previous Story and the theory of electrical phenomena. In both cases the laws governing the behavior of large collections of particles were discovered first: the laws of gases in atomic and molecular theory and, for electrical phenomena, the laws of the electric current. It was much later that the essence of these laws was deciphered. The properties of gases were deduced from the properties of micro-particles (atoms and molecules); electrical phenomena also turned out to be determined by the properties of individual micro-particles, i.e. electrons. With the development of physics at the end of the last century, it became clear that the two disciplines, for all their apparent dissimilarity, had very much in common, and it was established eventually that they come from the same origin—another evidence for the fundamental unity of nature.

In broader historical terms, however, the idea of the atom is much older than that of the electron—it was discussed as early as in ancient Greece and, being only a guess, greatly contributed to the evolution of scientific thought. The notion of "smallest electrical particles" appeared as late as eighteenth century as no more than a vague and blurred conjecture, and its way to recognition was by far more difficult. No wonder here—just remember the numerous disputes on reality of atoms. And this time the existence of even smaller particles was proposed, which certainly made them much more difficult to discover and study. Even to form a mental picture of them was psychologically impossible.

First observations of electrical phenomena. As far back as about 600 B.C., Thales of Miletos discovered that rubbing a piece of amber makes it capable of attracting small light objects (feathers, for example). For more than two thousand years it was the only observation to characterize the new physical phenomena. As to the term "electricity", it appeared for the first time as late as 1600, in a book by W. Gilbert, the court-physician to Queen Elizabeth. According to his definition, "electrical bodies are those which are attracted like amber" ("electron" is Greek for amber). Gilbert discovered that a glass rod is electrified when rubbed by silk. It is characteristic of the time that, being well aware of magnetic properties exhibited by some substances, Gilbert failed to see any link between electrical and magnetic phenomena. For a long time afterwards, these phenomena were studied as absolutely independent of each other

It was only in the eighteenth century that the studies of electrical phenomena began to gather momentum. In 1729, S. Gray subdivided all bodies into two large categories, i.e. the conductors of electricity and insulators. Du Fay, of France, observed that sealing-wax rubbed by fur is electrified like a glass rod, but in some opposite sense, which enabled him to define "glass" and "rosin" types of electricity. It was he who first established that like charges repel and opposite charges attract each other.

The first attempt to explain electrical phenomena was undertaken by the American physicist Benjamin Franklin in 1747. He believed that they were due to some "electrical liquid" ("fluid"), a necessary component of all material bodies. A body with too much of this fluid was considered to be positively charged and a deficiency of the fluid resulted in a negatively charged condition. From the fact that pieces of glass and silk, when rubbed together, acquire different kinds of electricity, Franklin concluded that positive and negative charges are produced simultaneously and in equal amounts. It is worth emphasizing that for Franklin, electricity was quite independent of matter and just existed alongside with it.

Franklin was the first to suggest the atomistic, or grainy, nature of electricity: "Electrical matter is composed of particles that should be extremely small". Needless to say, it was absolutely impossible, at the time, to test his hypothesis by experiment.

The remarkable insight into the nature of electrical phenomena was shown by M.V. Lomonosov. He suggested that "outside an electrified body there is some intangible matter which produces this effect". The deep intuition of the great Russian scientist enabled him to foresee nothing less than the modern idea of electrical field!

The basic concepts of the electricity theory were only formulated with the beginning of quantitative studies in the area. In 1785, a French physicist Charles Coulomb succeeded in finding experimentally the law of interaction between electric charges:

$$F = k\frac{q_1 q_2}{r^2},$$

where q_1 and q_2 are the electric charges, r is the distance and F, the force of interaction between them, and k is a coefficient (not to be confused with Boltzmann's constant). This law had been established long before the nature of electricity was discovered.

The slow progress in the science of electricity was largely due to the fact that at the time there was no practicable source of electric current. It was really a breakthrough when such a source was invented in 1800 by the Italian scientist Allessandro Volta. It was a pile of alternating zinc and silver discs stacked one on the other, each pair separated from the adjoining pair by a cloth or paper disc saturated in brine. With this discovery, the transmission of current through various substances became a subject of intensive studies.

The first remarkable result to be found (as soon as in 1801) was that, when a current passes through salt solutions, the electrodes are being covered with a layer of substance (Fig. 11). The effect came to be known as electrolysis and was the first indication of the fact that matter and electricity had something in common. The great English physicist Michael Faraday (1791-1867) performed the most significant quantitative studies in this new field. His "law of electrolysis" states that the mass of a substance that appears on an electrode is proportional to the current intensity and time. He showed further, that in order to obtain on an electrode a mass of substance equal numerically to M/n (M being the molar mass of the substance and n—its valency), a strictly determined amount of charge should be passed through the electrolyte. That was how

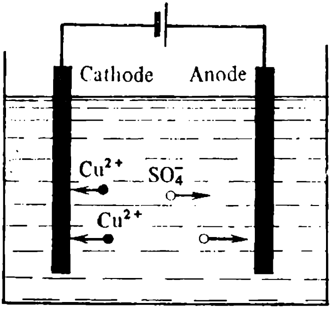


Fig. 11

another fundamental physical constant F came into science, later to be called *Faraday's number.* Its value was measured to be

$$F = 96\,484.5\ \mathrm{C \cdot mole^{-1}}.$$

The analysis of the phenomenon convinced Faraday that the true carriers of electrical forces were not some obscure electrical liquids but atoms—the particles of matter. He claimed that the atoms were somehow endowed with electrical forces. Faraday's studies on electrolysis were of major importance for the development of electronic theory.

Faraday was the first to discover the influence of medium on the interaction of electric charges. Introducing a new characteristic of medium, the dielectric constant ε, he rewrites Coulomb's law in the form

$$F = k\,\frac{q_1 q_2}{\varepsilon r^2}.$$

As was the case with Newton, Faraday would not accept the idea of action-at-a-distance. (You may remember that Newton did not believe that two masses could gravitate with nothing between them.) From his vast experience in electrical and magnetic studies, Faraday abstracted an entirely new concept of the electromagnetic "field" (he spoke of "lines of force"). For him, this was a material medium (filling "empty" space) through which, from point to point, the electric and magnetic interaction is transferred.

Electricity and magnetism unified. In 1820, Hans Christian Oersted, in Copenhagen, discovered experimentally the relationship between electricity and magnetism which had always been thought to have nothing to do with each other. Opening and closing an electrical circuit, he noted oscillations of a compass needle placed nearby. This discovery was followed by intensive and fruitful investigations in the field. The French scientist A. Ampére found out that the interaction between electricity and magnetism could only be observed if there was an electric current (that is, electricity in motion) but the static electricity produced no effect of this kind. In Faraday's miracle-working fingers a current-carrying wire starts to revolve around a magnetic pole—the first electrical motor in history. Faraday produced the first ever generator of electrical energy: pushing a magnetized iron core into a coil, he registered a current in the coil's winding. Electricity and magnetism became interconnected so closely that a new branch of science came to existence, i.e. electromagnetism.

Maxwell's equations. It was the English physicist James Clerk Maxwell (1831-1879), who had been destined to crown the theory of electromagnetism with his theory of electromagnetic phenomena. The equations he formulated (now studied in college physics courses) link together electrical and magnetic characteristics of the field. What makes the equations so extremely valuable is that they allow to obtain theoretically the results of high practical importance. Up to now, they are the starting point of all calculations of electromagnetic phenomena. A particular result which is of interest for us is that, according to Maxwell's equations, the electromagnetic field propagates in vacuum as an undamped wave (Fig. 12). This theoretical result was later confirmed most unambiguously by the experiments of Heinrich Hertz.

When employing his equations for a number of specific problems, Maxwell was able to evaluate c, the coefficient of proportionality entering these equations:

$$c = 3 \times 10^8 \text{ m/s}.$$

Numerically, the value of c turned out to be equal to the speed of light. So great was Maxwell's confidence in his equations that this apparently casual fact led him to the most significant conclusion: *light is the electromagnetic wave.* We shall see in the Fourth Story that future developments brilliantly confirmed this most audacious prediction of the genius.

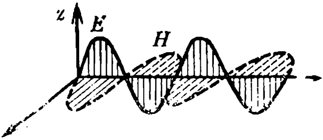


Fig. 12

Let us summarize, what we now actually know about electrical phenomena. Basic laws of interaction are studied, the relationship is established between electricity and magnetism, Maxwell's equations of electrodynamics are formulated. Here we have the mathematical frame of the theory, but the question remains to be answered: what is the nature of electricity? What is electricity: a liquid or some little elementary carrier (particle)? For most physicists of the time that was not a problem to bother about—they just took Maxwell's equations, used them for solving various problems and were quite satisfied. To look deeper was something beyond the code of decency.

DISCOVERY OF THE ELECTRON (ANALYSIS AND SYNTHESIS)

Throughout the nineteenth century, the studies of electricity and of the structure of matter went in parallel. One of the most spectacular achievements of the day was, of course, the discovery of the electron, made first "on paper", just through analysis of information obtained in these apparently different fields.

Analysis. In Faraday's time it occurred to no one, to use his electrolysis laws for studying the nature of electricity. But certainly scientists are not to be blamed too much. Don't forget that the very existence of the atom was then a matter of belief (or disbelief) and the first measurements of Avogadro's number were performed as late as in 1873. So far, there was only a vague idea floating in the air of something called electric charge. It was generally believed that a charge resides on a charged body and acts upon other charged bodies at a distance, very much like the Earth acts on the Moon. But, of course, the electrical forces, unlike gravitational, could also be repulsive.

The first measurements of Avogadro's number made physicists reconsider their scientific position. Had not they been too preoccupied with characteristics of the electric field and too little interested in its nature? Is it possible that there exists a material carrier of electricity? Hermann Helmholtz was the first to clearly express this idea in 1881: "If we have to assume the existence of atoms of chemical elements, we cannot but conclude that both positive and negative electricity are themselves subdivided into elementary portions which behave as atoms of electricity."

It was the Irish physicist G.J. Stoney (1826-1911) who first evaluated this "elementary portion" of electricity. His reasoning was extremely simple. We know from electrolysis that to deposit one mole of a monovalent element, we require 96 484.5 C of charge. But one mole contains 6×10^{23} atoms. It is then obvious that, on dividing Faraday's number F by Avogadro's number N_A, we obtain the amount of electricity which is necessary for one atom of the substance to appear on the electrode. Let us denote this amount as e:

$$e = \frac{F}{N_A} = 1.6 \times 10^{-19} \text{ C.} \tag{3}$$

In 1891, at the suggestion of Stoney this minimum portion of electricity was called "electron". The term was readily accepted but what it actually meant was far from clear.

To begin with, in electrolysis process we are dealing with the transfer of a large number of atoms. It was argued, therefore, that what Stoney obtained was no more than an average value of the electron's charge. The existence of a definite minimum portion of electricity remained open to question.

Note, on the other hand, that the term "electron" had been introduced by Stoney with no hint whatsoever as to the mass or inertia to be associated with this amount of electricity. So far, no word had been said about a particle and it was only a certain portion of charge that was discussed—a quantum of charge, to speak in modern language.

But in spite of all these doubts, the job was done: if only theoretically, the electron was discovered and could no longer be overlooked. The magic numbers, universal physical constants F and N_A, in alliance with intellectual efforts of scientists, produced one more constant, the electron's charge e. Isn't it a further demonstration of the role played in physics by universal constants?

Synthesis. But what about the "real" discovery of the electron? It so happened that the existence of the electron as an independent physical particle was established in an altogether different area, i.e. in the studies of physical phenomena accompanying the flow of current through gases. Here again we have a chance to admire the keen insight of great Faraday who initiated these experiments in 1838. He strongly believed they should give a valuable information for the theory of electricity, and it turned out to be the case. It was these studies that led to the discovery of the cathode rays and, ultimately, to the discovery of the electron. It is worthwhile therefore to describe these experiments.

In the middle of the nineteenth century the technical progress gave scientists a new and powerful tool for further research, the pump. It was now possible to evacuate gas (or at least part of it) from glass tubes, thereby producing a vacuum. A German physicist Julius Plücker reported in 1869 that electric current passed freely through a glass tube with almost all of the air pumped off from it. What was more, the glass surface opposite to the negatively charged electrode (cathode) displayed a glow, apparently due to some previously unknown invisible rays. They were called, quite reasonably, the cathode rays and soon became a primary object of scientific research. If only reluctantly, Nature gave away its secrets. The English physicist W. Crookes found that the objects placed on the way of the cathode rays cast shadow which meant that the rays travelled in straight lines. Under the action of cathode rays, a toy wheel-paddle could be made to rotate on its axle, with a necessary conclusion that some mass should be ascribed to the rays. J. Perrin found that the cathode rays transferred negative charge. It was also reported that the rays deflected in a magnetic field or in the field of a charged electrical capacitor. All these findings implied that the cathode rays should be a stream of negatively charged high-speed particles. An opinion was even expressed that the particles might be no less than the "physical foundation of the Universe" (Crookes, 1874).

To make sure that the cathode rays were indeed negatively charged particles, direct experiments should be carried out, to measure their mass and charge. They were undertaken in 1897 by the English physicist J. J. Thomson. A schematic view of his experiment is shown in Fig. 13. The cathode-rays moved in the electric field of a capacitor with a superimposed magnetic field. Calculations show that in an electric field of strength E the assumed particles are deflected through an angle:

$$\Theta = \frac{eE}{m} \frac{l}{v^2},$$

where e is the charge of the particle, m is its mass, l, the length of the capacitor and v, the (unknown) velocity of the particle. For magnetic field B, the deflection angle α may be shown to be

$$\alpha = \frac{eB}{m} \frac{l}{v}.$$

At $\Theta \approx \alpha$ (which was the case in Thomson's experiments) one could find v and then calculate

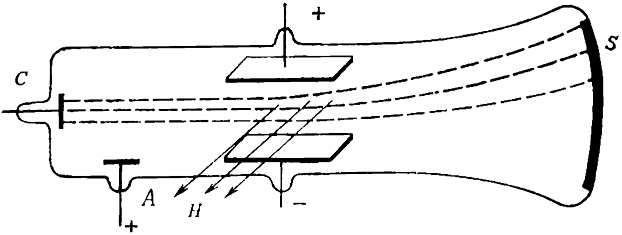


Fig. 13

the ratio e/m, i.e. the specific charge of the electron. The experiments showed e/m to be always the same whatever the gas species. Another result was that in cathode rays the e/m ratio is about 10^3 times that of the (lightest possible) hydrogen ion H^+. Thomson concluded from this that the mass of the cathode-ray particles was 10^3 times smaller than that of H^+. Thomson was the first to formulate clearly the idea of a new elementary particle of matter and is regarded by right as the discoverer of the electron.

The electron in other phenomena. When a scientist knows for certain what he is looking for, when there is a guiding star to follow, his task becomes much easier. It is quite understandable, therefore, that the electron was very soon discovered in a number of other physical experiments.

As early as 1887, Hertz discovered the photoeffect. A metallic plate was illuminated by light and, as an electroscope showed, lost some amount of charge (see Fig. 14). The assumption was that light knocks out negatively charged particles from the surface of the metal. Taking up the idea of Thomson's experiment, Philipp Lenard found in 1899 that the particles produced by the photoeffect had the same specific charge as the electron did. Thomson himself was intrigued enough to repeat these experiments. It was shown beyond any reasonable doubt that it is just the emission of electrons that is the essence of the photoeffect. It was another evidence for the existence of the electron as an independent particle.

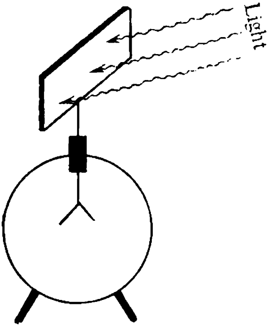


Fig. 14

Radioactivity was another phenomenon for electrons to manifest themselves. It was discovered in 1896 by A. H. Becquerel of France. He noticed that uranium salts emitted some invisible rays that caused blackening of a photographic plate. Further investigations showed that in a magnetic field these mysterious rays were splitted into three components called alpha-, beta- and gamma-rays. Gamma-rays passed through the field undisturbed, while alpha- and beta-rays, judging from the way they were deflected, behaved like positive and negative charges, respectively (see Fig. 15). In 1900, by measuring the specific charge of beta-particles, Becquerel found that beta-rays were in fact a stream of electrons. There was no doubt now that the electron was indeed an independent particle and, even more, a building block of the Universe.

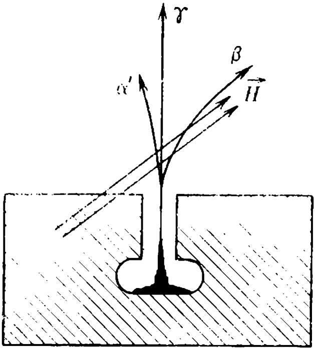


Fig. 15

NOBEL PRIZE TO EVERY STUDENT

Inevitably, the discovery of the electron brought about further questions. Could we conceive of any experiment to provide a direct evidence for the existence of an elementary portion of electricity? We have seen earlier that, strictly speaking, electrolysis data provide what may well be considered as an averaged charge of the electron. But the same is true for the cathode-rays. Can we measure the electron's charge and mass separately? Are there any experimental situations in which the mass of the electron could manifest itself? Quite a lot of problems!

The honour of direct measurement of the electron's charge belongs to the outstanding Ameri-

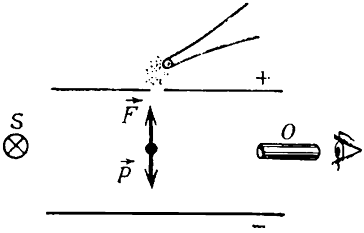


Fig. 16

can physicist Robert Millikan. The idea of his experiment (performed in 1909) is as simple as it is convincing. The experiment consisted of producing very fine oil droplets in the space between two horizontal capacitor plates (see Fig. 16). When sprayed by a pulverizer (through a window), the droplets acquired charge (due to friction) and their behavior was therefore dependent on whether or not there was a voltage applied across the plates. The droplets were illuminated by a light source S and observed through an objective. In the absence of voltage, a given droplet was observed to fall at a speed v_1 given by

$$v_1 = fP,$$

where P is the weight of the droplet and f is a proportionality factor. When an electric field E was switched on, the velocity of descent v_2 was defined by

$$v_2 = f\,(qE - P),$$

where q is the charge of the droplet. (It is assumed that gravity and the electric field act in opposite directions.) It follows from these equations that

$$q = \frac{P}{Ev_1}\,(v_1 + v_2).$$

To measure the charge of a droplet, Millikan employed the X-rays discovered in 1895 by Wilhelm K. Roentgen. These invisible rays are emitted by solids bombarded by a stream of fast electrons. A remarkable property of X-rays is their ability to ionize air. The ions of the air are captured by the droplets whose charge therefore is altered. If the charge of a droplet, with an ion attached, is q' and its velocity is v_2', the change in charge is

$$\Delta q = q' - q,$$

or finally

$$\Delta q = \frac{P}{Ev_1}\,(v_2' - v_2).$$

For a given droplet, the quantity $P/(Ev_1)$ is a constant. It turns out then, that in order to find the charge of a droplet, two quantities are to be determined: the distance travelled by the droplet and the time the droplet passes this distance. But both length and time can be measured easily and, most important, with high accuracy.

Millikan found in his experiment that, whatever the size of the droplet, Δq was always an inegral multiple of a minimum charge e

$$\Delta q = ne,$$

where n is a whole number. The atomic nature of electricity was now beyond any doubt.

From experiments and calculations, e was found to be

$$e = 1.6 \times 10^{-19}\ \mathrm{C}.$$

The reality of the minimum portion of electricity was proved. For these experiments, Millikan was rewarded the Nobel prize in 1923. Today, for every college student, these remarkably simple experiments are just the matter of everyday laboratory routine.

Experiments made by Ioffe. The fact of step-like changes in electric charge was confirmed by the noted Soviet scientist A. F. Ioffe. In his experiments, the object under study was a tiny speck of metallic dust. The force of gravity being counterbalanced by an electric field, the speck was suspended motionless between the plates of a capacitor. When illuminated by light, the speck displayed a step-like change of its charge, due to liberation of electrons from the surface of the metal (photoeffect). The value of e coincided with that found by Millikan.

How much does an electron weigh? Using the value of e and Thomson's result for the specific charge of the electron, $\frac{e}{m}$, we are now in a position to calculate the electron's mass m_e. We obtain

$$m_e = 9.11 \times 10^{-28}\ \mathrm{g}.$$

It turns out that the electron is 1836 times lighter than a hydrogen atom!

A direct proof that the electron is indeed endowed with mass was provided by American experimental physicists Stewart and Tolman, in 1916. An ordinary coil of conducting wire was first set into rapid rotation and then abruptly stopped. If indeed the electrons have a mass (and hence, inertia), they should persist in their motion (or, in other words, an electric current should flow) for some time after the coil has stopped, which indeed proved to be the case.

Summing up, we can say that the discovery of the electron was only possible through an analysis of an extremely large number of experimental facts. It was Thomson who displayed the deepest insight into the problem and he is certainly the one to be regarded as the author of the discovery. With Millikan's experiments, not only the existence of the minimum portion of charge became a fact, but also its value and mass were measured. The discovery of the first elementary particle, the electron, was an event of extreme importance for physics; the quantum (or discontinuous) nature of electric charge was proved experimentally. The discovery of the electron caused intensive studies of its properties and, of course, new problems were again round the corner.

THE TROUBLESOME MASS

From its earliest days in science, the electron brought about quite a number of surprises to puzzle physicists. Novel ideas had come into physics. Before the advent of the electron, it was a matter of common belief, just as it was in the days of the ancient Greeks, that the atom was indivisible. And all of a sudden, it is declared that an independent particle exists whose mass is much less than that of hydrogen, the lightest atom of all. A particle that has a charge of its own and is somehow a part of the atom itself. Physicists were faced with utterly new problems, of which *the structure of the atom* was now on the top of the agenda. The inner structure of matter was thus in focus again but this time on a much deeper level. We shall discuss later the atomic structure and all the problems involved. For the moment, however, let us take a closer look at the mass of the electron, for here lies one of the deepest problems posed by this enfant terrible of physics.

The reader may have noticed that it is not the mass of electron that enters the table of universal constants, but rather its *rest mass.* So far, we have not yet discussed mass as a physical characteristic of a body. But certainly we encounter here one of the most difficult problems in physics. It is worth emphasizing that it was the problem of the electron's mass that led Einstein to his famous theory of relativity. And, on the other hand, the effects associated with the mass of electron provided the most convincing proof for Einstein's theory.

Electromagnetic mass. When talking about the mass of a body, no one cares usually of the charge of the body or its velocity when the mass is measured. For a man in the street, this is absolutely immaterial. However, as early as in 1881 J. J. Thomson suggested that the inertia of a body is determined not only by its mass but also by the charge. His reasoning is quite straightforward. Indeed, a moving charged body produces an electric current. This, in turn, produces a magnetic field H. A change in the velocity of the body leads to a change in the strength of the current as well as in the magnetic field. But the change in H gives rise to an electromotive force. We see then, that if a charged body moves faster, the induction electromotive force will hinder its motion, which means, in fact, that the charged body acquires an additional mass of electromagnetic origin.

How large is the electromagnetic mass? Dropping all the details let us write at once the final result. For a sphere of radius r the additional mass is

$$\Delta m = \frac{2}{3} \frac{q^2}{r},$$

where q is the charge on the sphere. If a sphere has a radius $r = 1$ cm and a potential $U = 3 \times 10^5$ V, the additional mass will be

$$\Delta m = \frac{2}{3} \frac{q^2}{r} = \frac{2}{3} \frac{(CU^2)}{r} \simeq 10^{-15} \text{ g}.$$

It would appear that the value of Δm is too small to deserve anything but a complete neglect. But Thomson's conclusion that the mass of a body depends on its velocity is very important. In view of the extreme smallness of Δm, it was clear that this effect could only be found for extremely small particles moving at very large speeds. We find this statement in Thomson's 1893 paper, four years before the discovery of the electron, but does not it seem that he was already well prepared to the discovery?

The electron having been discovered, it was now possible to verify Thomson's prediction. W. Kaufmann, in 1906, was the first to establish the dependence of the electron's mass on its velocity. He investigated the behavior of an electron beam, coming from a radioactive source, in a superposition of an electric and a magnetic field (see Fig. 17, where the velocity of the electrons is normal to the plane of the drawing). According

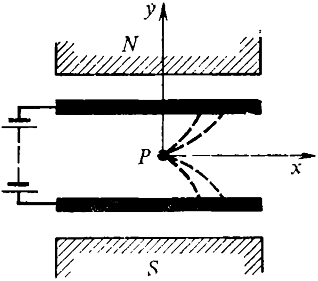


Fig. 17

to theory, the vertical deflection of the beam, y, and its horizontal deflection, x, are related to each other

$$y \propto \frac{m}{e} x^2,$$

that is a figure the electron beam draws on the screen, should be a parabola. What Kaufmann observed, however, was something different. The point was that electrons travelling at different velocities, had different values of e/m ratio. The fact of the mass-velocity dependence was confirmed by experiment.

That was a complete surprise. The experiment urgently needed an explanation. It was necessary first to obtain the dependence $m(v)$ theoretically and then to verify it by experiment. As a matter of fact, the dependence had already been found and in two different forms. Back in 1902, the German scientist M. Abraham, considering the electron as a round and nondeformable ball and using the laws of classical mechanics, obtained the dependence $m(v)$ in the form:

$$m=\frac{3m_0}{4\beta^2}\left(\frac{1+\beta^2}{2\beta}\ln\frac{1+\beta}{1-\beta}-1\right),$$

where m_0 is the rest mass of the electron, $\beta = v/c$ (c is the speed of light).

H. A. Lorentz attacked the problem from another angle. To account for the negative result of Michelson's experiment (see the Fourth Story), he assumed that the length of a body along the direction of its motion contracts by a factor of $\sqrt{1-\frac{v^2}{c^2}}$. As a result, mass also showed a dependence on velocity, but in somewhat different form:

$$m=\frac{m_0}{\sqrt{1-\beta^2}}. \tag{4}$$

The same formula, although from entirely different positions, was obtained by Albert Einstein in 1905, in the framework of his relativity theory.

It was now up to experiment to decide, which of the two expressions was actually correct. First experiments by Kaufmann were in favour of Abraham's theory, disagreeing with common result of Lorentz and Einstein. Some physicists argued, however, that Kaufmann's experiments had not been sufficiently accurate. The most skilled experimenters took the matter into their hands and it was shown that Kaufmann's equipment was inadequate (although it took ten years for this to be fully realized). It now became clear that formula (4) was correct.

Some remarks may be worthwhile here on the nature of the $m(v)$ dependence. And as well on the value of various physical theories. The theories of Abraham and Lorentz proceeded from a number of ill-founded assumptions and were devised *ad hoc*, just to fit new experimental facts. Not so with Einstein. While it is true that his $m\ (v)$ dependence coincides formally with that of Lorentz (expression (4)), it results from an entirely new

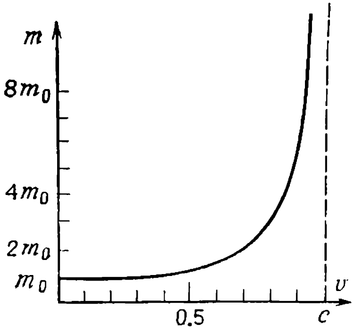


Fig. 18

theory, in which the problems of motion are treated on by far more profound basis (we shall discuss the subject in more detail in our next Story). Having radically modified old and, from Newton's days, deep-rooted views on space and time, Einstein extended the physical meaning of mass. It follows from his theory that at large speeds of motion, the mass of any physical object does not remain constant but increases (see Fig. 18). It also follows from his formula (4) that *a body can never move at a speed larger than that of light.*

In this Story, we have met the speed of light more than once. First, it appeared as the (theoretically predicted) propagation speed of electromagnetic oscillations (see p. 71). Now we meet it as the maximum possible speed of a physical object. But there is much more to say about this physical constant and its role in modern physics. It was in the struggle for the better understanding of this constant that physicists were forced to review old ideas about space, time, mass and energy. It is this constant that lies at the heart of a new science—the theory of relativity created by Einstein. This theory was able to resolve problems that remained unanswered from the age of Newton, the problem of gravitation among them. It will be only appropriate to devote our next Story to a discussion of the fundamental importance of the speed of light.

FOURTH STORY

The Puzzle or the Tale of the Speed of Light

HAVE YOU EVER SOLVED PUZZLES?

Certainly you must have solved puzzles in your life, haven't you? Just remember what a queer gamut of feelings you go through in this thrilling process. First you are at a complete loss, perplexed and frightened by what seems an absolutely impregnable problem. Then you start the search for the solution, a tedious, painstaking and time-consuming process, and often disheartening too, for it is full of false starts and dead ends. But there comes upon you a firm sensation that you are just on the right track, and at last, you've got the answer! You are proud, you are quite sure of yourself and certainly you will solve now any problem your cunning friend has up his sleeve for you.

If you come to think of it, the physical meaning of the speed of light was, in a way, the puzzle Nature posed before science even though on a much greater and more serious scale. For certainly it was not just a game for amusement, the more so since it lasted for two millenia. But all the same, the way that science has gone to the understanding of light has much in common with puzzle-solving. There were uncertainties and doubts, quite a lot of mistakes and, grain by grain, the accumulation of experimental evidence, and the first flashes of real knowledge, all to be theoretically interpreted by Albert Einstein, the greatest scientist of the twentieth century. It is no exaggeration to say that no other constant in physics is so fundamentally important as the speed of light.

Reading the previous Story you may have noticed a logic lapse there. While discussing two constants associated with the electron, another universal constant was also mentioned in passing—the speed of light. Two different aspects of this concept were pointed out. First, the electromagnetic wave propagation speed, second, the maximum possible speed of the electron. But we shall see later that the physical significance of the concept is in no way limited by these two facts. In the search for the proper interpretation of this constant man has found and harnessed new forces of nature. A new theory of space and time, the theory of relativity, was created by the genius of Einstein. Its conclusions were too paradoxical to be easily accepted by the contemporaries, but experiment proved its validity and today it is a fully recognized theory. While the puzzles are solved "just for fun", the solution of the problems associated with light has given us a lot for our practical life. It is only natural, therefore, if we devote a Story of this book to the analysis of this most important physical constant—the speed of light. In doing so, we shall not be able, of course, to discuss all the problems involved—

on the contrary, we shall encounter new problems and new physical constants. The puzzles of nature are innumerable and ins't it possible that some of them will be solved by our reader?

A VICTIMLESS DUEL

When asked, what is light, hardly anyone will be too quick to answer. We are just lucky to be born with light around us. We've got used to it that the Sun will rise tomorrow in due time and the day will come to be followed by the charming quietness of the evening. In spring days get longer, the benevolent rays of the Sun bring more and more of its energy onto the Earth. The snow begins to thaw, meadows and woods come back to life and the beauty of blossoming flowers is again irresistible... Every one of us will agree that light is the foundation of life on the Earth. But isn't it a little boring to ask questions like "what is light"? Well, not for a man of inquisitive mind, the more so—for a physicist.

From the earliest days of man, the nature of light was for him the most intriguing mystery, but none of its secrets did nature keep so jealously. Strange, isn't it, especially taking into account that light gives us, through our vision, more information about the outside world than all other senses provide together. Light always was, and is, the most powerful tool for studying nature —just remember, for example, the observation of planetary motions that opened the way to Newtonian mechanics and, in fact, to all modern physics.

For the ancient Greeks, certainly, light was not the problem to be ignored. Some of them thought it to be something originating in human eye: we see things by directing on them the flow of light. Objecting to this "emanation" theory, Aristotle asked why, if the emanations produce vision, we cannot see in darkness. Democritos, in the spirit of his atomistic hypothesis, believed that the atoms, coming from'a luminous body act on the surface of the eye, thus producing visual sensations. But, of course, debates were to remain debates, and theories—theories (or even speculations) until the advent of the Experimental Method.

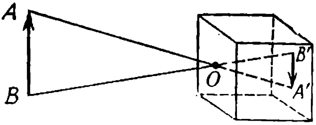


Fig. 19

Optics gets independence. The first observational data were scarce and sporadic. About 300 B. C., Euclid established that light travels in straight lines. In the second century of our era, Ptolemy studied experimentally the refraction of light in going from one medium to another; he failed, however, to formulate the refraction law. Roger Bacon, in the thirteenth century, was the first to notice the magnification of objects viewed through a flat-convex lense.

In the fifteenth century the first optical instrument appears, the camera-obscura (see Fig. 19) capable to produce the image of a luminous object (which had always been considered a prerogative of the human eye). The similarity between the processes occurring in the human eye and in the camera-obscura was pointed out immediately by Leonardo da Vinci. But the significance of this invention is that the camera-obscura, as S.I. Vavilov put it, "resolutely separated light from vision". In the sixteenth century optics (which means literally "the science of vision") became an independent branch of physics.

In the seventeenth century, a number of very important events took place in optics. To cite but a few examples, we can enumerate the refraction law announced by Rene Descartes in 1637; the first descriptions of the light diffraction experiments, by Grimaldi; optical discoveries of Newton and Huygens. New experimental data needed explanations, and explanations were proposed, but the puzzle was that optical phenomena seemed to be explained equally well in two totally different ways. One theory was based on the idea that light is a wave process, the advocates of the other thought light to be a stream of particles (corpuscles) travelling in straight lines. Let us take a simple example of refraction, to see what explanation each theory proposes for the effect.

Light refraction in the corpuscular theory. Let light be a particle falling on the division surface between two media *1* and *2* (see Fig. 20). We may decompose its velocity in both media into vertical and horizontal components. Clearly, the value of the horizontal component does not change in going from one medium to another, so that

$$v_{1(\mathrm{II})} = v_{2(\mathrm{II})},$$

or

$$v_1 \sin \Theta_i = v_2 \sin \Theta_r,$$

where Θ_i and Θ_r are, respectively, the angles of incidence and refraction. We thus find:

$$\frac{\sin\Theta_i}{\sin\Theta_r}=\frac{v_2}{v_1}=\text{constant}.$$

But the velocity of light in a medium relates

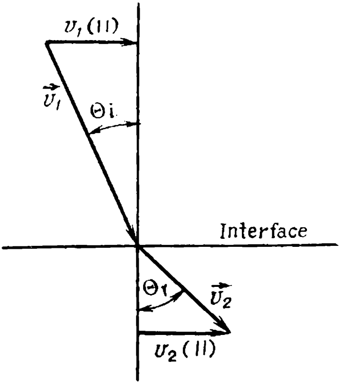


Fig. 20

to its velocity in vacuum as

$$v=c/n,$$

where n is the index of refraction. We thus come to the law of refraction in its familiar form:

$$\frac{\sin\Theta_i}{\sin\Theta_r}=\frac{n_1}{n_2}$$

Refraction law in the wave theory. If light is considered as a wave, the process of refraction can be described in the following way. Look at Fig. 21. Here *AC* is the front of the incident wave, whose wavelength λ_1 is equal to the length *BD*. By the time when point *D*, in its propagation, reaches point B, the wave excited at point A will pass in the second medium the distance AE equal to the wavelength of light in this medium, λ_2. The incidence angle Θ_i may be defined by the relation

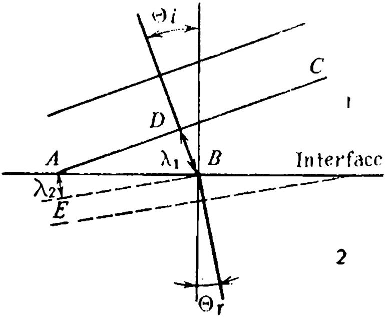


Fig. 21

$$\sin \Theta_i = \frac{\lambda_1}{AB},$$

while the refraction angle Θ_r, by

$$\sin \Theta_r = \frac{\lambda_2}{AB}.$$

From this, the refraction law is

$$\sin \Theta_i / \sin \Theta_r = \lambda_1/\lambda_2.$$

Since $\lambda_1/\lambda_2 = v_1/v_2$, we obtain

$$\frac{\sin \Theta_i}{\sin \Theta_r} = \frac{v_1}{v_2}.$$

The ratios of the sines involved in the above equations, can be easily measured, i.e. by observing a beam of light falling onto the surface of a liquid (say, water) from the air. This simple experiment shows, as you know, that the refraction angle is smaller than the incidence angle, so that

$$\frac{\sin\Theta_i}{\sin\Theta_r} > 1.$$

But then we can distinguish between the two theories. By the corpuscular theory, the velocity of light in the air (v_1) should be smaller than in the water (v_2), by the wave theory, just the other way around. To see, which of the theories is correct, just measure these velocities and you will have the answer. So you will, but don't forget about the limitations of experiment. You have not only to measure the speed of light, which is quite a problem in itself, but, what is more, to detect the speed change in passing from one medium to another. It was not until 1862 that these experiments were performed and even then the final answer was not found.

The competition between the corpuscular and wave theories of light lasted for more than two centuries. It was a struggle of principle in which best scientific minds were involved and no weak point in one theory remained unnoticed by the other side. The wave theory was advanced by the Dutch physicist Christian Huygens (1629-1695). But, Newton objected, if there is a (light) wave then, certainly, there should be a medium in which the wave is transmitted. To save face, Huygens was obliged to postulate some unknown hypothetical medium, the "ether". For Huygens, this was a substance that filled all space and penetrated all material bodies. But "what is the ether," Newton asked him angrily, "I can neither see nor feel it". If light is considered as particles, there is nothing it requires for propagation—why should we make it waves and introduce some mysterious substances? (You remember, of course, that Newton himself had been disappointed in ether after many fruitless attempts to use it for his theory of gravitation.)

Still Huygens was not to be outdone. It is a well-known fact, he argued, that two beams of light do not interact with one another when intersecting. How could this be reconciled with the idea of light being a stream of particles? To which Newton replied: the wave theory cannot account for the fact that light travels in straight lines since the waves on the surface of water are not stopped by an obstacle but very soon appear behind it.

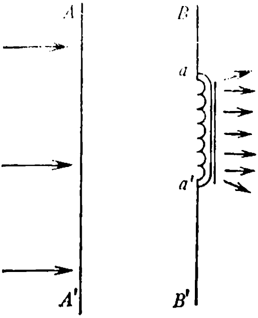


Fig. 22

This is not to say, however, that Newton was dogmatic in his corpusular views. A book by Grimaldi, in which the diffraction of light was described (see Fig. 22), did not remain unknown to Newton, and he saw only too well that the phenomenon was inconsistent with the corpuscular theory. The question of the nature of light remained unclarified for him and other approaches were not altogether impossible. In Newton's view, the true theory should combine harmoniously the achievements of the wave and corpuscular

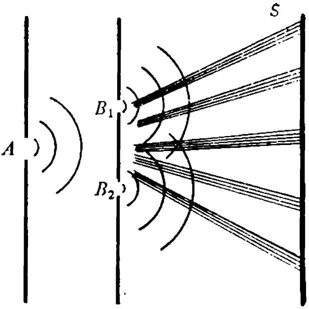


Fig. 23

theories. The great scientist was right, as later science has demonstrated. But at the time and long afterwards, light was a mystery... There was "not a sufficient number of experiments!"

Direct proof of the wave nature of light. In 1801, Thomas Young discovers the phenomenon of the optical interference (see Fig. 23). He observes, namely, that if a monochromatic light is shone on two parallel slits the screen beyond them displays alternating dark and bright bands. The only way to explain this effect was to adopt the wave concepts. It was the French scientist Augustin Fresnel who revived and developed them. In his experiments he studied various cases of diffraction and in his theory he was able to give a quantitative description of diffraction processes. Of particular importance was his result that the straightness of light propagation could well be explained on the basis of the wave theory. The phenomena of diffraction and interference provided strong arguments in favor of the wave nature of light. The wave theory definitely took the upper hand (for a time at least). But, of course, waves needed a medium to pass through and the old problem of the ether once again emerged.

What was worrying, the properties of ether appeared to be hardly, if at all, compatible with one another. On the one hand, the ether should be very thin, being supposed to penetrate all material bodies. On the other, in order to sustain the light oscillations, its elasticity should be comparable with that of solids. What was the most embarassing, however, ether was absolutely unobservable, with all the attempts to detect it ending in failure. The question of ether as the material carrier of the light waves was becoming increasingly important for physicists.

Electromagnetic theory of light. What made the difference between the wave approach of Fresnel and the corpuscular one of Newton, was in fact that they considered different mechanisms for the transfer of light. In the evolution of optics this was an unavoidable stage since the most important laws of electromagnetism were to be discovered much later. It was only in 1864 that Maxwell advanced the idea of the electromagnetic nature of light.

That electrical and optical phenomena might be somehow interrelated, had been suggested actually before Maxwell. Back in the eighteenth century, M. V. Lomonosov considered it necessary to study the refraction of light in electrified bodies. In 1846 Faraday discovered the rotation of the plane of polarization of light under the action of a magnetic field, which led him to a hypothesis that light is the propagation of magnetic perturbations. We know from the previous Story

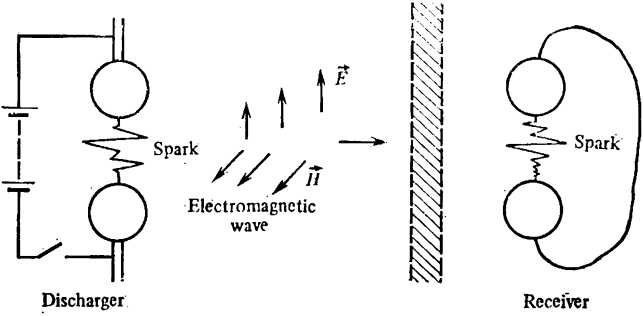


Fig. 24

that Maxwell, while analyzing his equations, arrived at the idea that light is the electromagnetic wave. This was directly confirmed by Heinrich Hertz in 1887. His experimental apparatus consisted of two well-polished metallic balls separated by a small air gap, as shown in Fig. 24. At the instant a high voltage was applied to the balls, a spark jumped, or, to put it another way, an alternating electric current passed through the gap. But, according to Maxwell's theory, an alternating electric current should induce electromagnetic waves. That this was indeed the case, was confirmed by another spark which was synchronous with the first one and was observed between the balls of a remote discharger (placed in a neighboring room). In a thorough investigation of the phenomenon, Hertz studied the reflection, refraction and interference of the electromagnetic radiation. His conclusion was: "The above experiments show that light, thermal radiation and electrodynamic wave motion are all the same".

The electromagnetic theory of light stood now on a firm experimental basis. And what about the ether? Well, the old "luminoferous" ether still was there, even though in a somewhat new guise: it was now the seat of electromagnetic oscillations. As Maxwell himself put it, "We have therefore some reason to believe, from the phenomena of light and heat, that there is an etherial medium filling space and permeating bodies, capable of being set in motion and of transmitting that motion from one part to another..."

Now that the electromagnetic nature of light had been established, the positions of the wave theory looked strong enough. But it is one of the ironies of physics that Hertz's experiment which served to corroborate Maxwell's theory of electromagnetic waves also contained data which proved later to be consistent only with a corpuscular interpretation of the electromagnetic radiation. Hertz observed, namely, that if one of the balls of the discharger was exposed to ultra-violet radiation the spark jumped at much lower voltages. The suggestion was that, some way or the other, the light falling on the metallic surface of a ball knocked electrons out from the metal (photoeffect). In the years 1888-1889 A. G. Stoletov, Professor at the University of Moscow, carried out detailed studies of this phenomenon and established all its main laws. He showed in particular that the current in the circuit (see Fig. 25) was proportional to the intensity of light. It was hardly surprising: the higher the energy of the light beam, the stronger is its action.

However, since the electric field strength of the light wave increases with intensity of light,

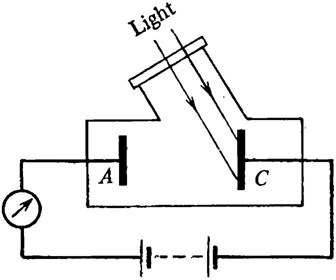


Fig. 25

it might well be expected that the maximum energy of outgoing electrons will also increase. Experiment showed nothing of the kind. If, on the other hand, we increse the frequency of the light while keeping its intensity constant, then at frequencies high enough the electrons should leave the metal with lower energy: they have some mass, after all, and should therefore be less sensible to higher frequency fields. This suggestion also proved to be wrong. The maximum kinetic energy of outgoing electrons increased linearly with the light frequency and was independent of the intensity.

Clearly, classical physics was in trouble and it was Albert Einstein who found a way out.

He suggested the existence of light particles, later to be called *photons*. Since maximum energy of outgoing electrons increases with light frequency, Einstein assumed the energy of a photon to be proportional to the frequency ν:

$$E = h\nu. \tag{5}$$

The coefficient of proportionality in this equation was later given the name of *Planck's constant*. (This is another universal physical constant and in the next Story we shall learn more about it). The photoeffect could now be explained in a simple and quite natural way. Einstein assumed that an electron absorbs one quantum of energy, that is, one photon, from the incident light beam. A quantity A of the energy $h\nu$ is required to remove an electron from the metal and the remainder $\frac{mv^2}{2}$ is the kinetic energy of the electron after it leaves the metal. We thus have

$$h\nu = A + \frac{mv^2}{2},$$

where v is the speed of the electron. This equation turned out to be in perfect agreement with experiment. Light behaved like a stream of particles and age-old arguments on its nature were once again rekindled.

Wave-particle duality. It was, indeed, a very embarassing and controversial situation. Light manifests itself as a wave in the experiments on diffraction and interference. It displays particle properties in the photoeffect and in the radiation or absorption of light by atoms (to be discussed in the Fifth Story). And yet, how can a particle be a wave? The two descriptions seemed to be completely at odds with one another but you can't get away from facts. The twofold nature of light was to be accepted: there was no other way out of the dilemma.

So, the long competition between the wave and corpuscular theories ended up with their alliance. This may seem rather disappointing. Indeed, if after so much effort two quite different theories have to be united—isn't it a defeat of science? Well, the answer is certainly "No". Quite to the contrary, that was a major step forward, a real breakthrough, as, one would hope, the reader will see later in the book.

IS THE SPEED OF LIGHT CONSTANT?

Finite or infinite? The properties we have just seen make light quite a remarkable physical phenomenon, don't they? But time has now come to turn to the main subject of this Story, to the speed of light, and, in particular, to its measurement. To begin with, is the speed of light finite or otherwise?

From the ancient Greeks down to the Middle Ages, the speed of light, if discussed, had nothing to do either with experiments or with observations for the simple reason that there weren't any. Still, the question was sometimes discussed or rather speculated on. Aristotle, for example, believed that light propagates instantly. In "Optics" by Damian (the first century A. C.) we read: "Propagation of light of an eye and of the Sun to the utmost boundaries of the heavenly sphere occurs instantly for ... we see the sky at the same instant that we look upwards." Not too convincing, is it? In the eleventh century, an

Arabic scientist Alhasen suggests that light travels at a finite speed.

Descartes (in the seventeenth century) assumed light to be a stream of particles (small balls) moving with an infinite speed. From what may be called a "mechanistic" model in which a ball (light) falls on the interface between two media, he was able to deduce the law of refraction. The theory of Descartes came under criticism, however. In an alternative approach, his contemporary Fermat made use of the (by himself proposed) minimum time principle. The actual path of light between two points, he claimed, differs from all other imaginable paths in that it is passed by light in shortest time possible. (It is interesting to note that the proposition met strong objections. If Fermat is right, his opponents argued, then light is endowed with "free will": it knows which way to go.) An implication of this approach was, of course, that the speed of light is finite. Whether the velocity of light was finite or infinite was therefore of crucial importance in the competition between the two theories. The answer could only be found in direct measurements.

First measurements of the speed of light. Galilei, the father of experimental physics, was the first to suggest a direct method to measure the speed of light. His idea was very simple. Two observers, each having a lantern, are placed several kilometers apart. One of them lifts the shutter of his lantern, thereby sending a light signal to the second observer. The latter at the instant he sees the light, opens his own lantern, to send a signal back to his colleague. The first observer measures the time from the instant he had opened his lantern to the instant he saw the back signal. The speed of light can then be calculated as

$$c = 2s/t,$$

where s is the distance and t is the time in question. The trouble was that the time t was too short to be measured, so that the first experiments by this method (performed in Florence) gave no conclusive results. What they showed, however, was that the speed of light was finite.

The Danish astronomer Olaf Roemer was the first to succeed in measuring the speed of light. For this purpose he used the eclipses of the Jovian satellite Io in 1676. It was well known in his time that, at different positions of the Earth in its orbit—which is to say at different times of the year—Io appeared from behind Jupiter with different delays, up to 22 minutes (see Fig. 26). "This time," Roemer explained, "light requires to travel the distance between the position of my first observation and my present position" (meaning, as shown in Fig. 26, the right and left positions of the Earth, respectively). The value of the speed of light could be found by dividing the diameter of the Earth's orbit by the time of delay. Since in Roemer's days the value of the diameter was not known exactly, the speed of light he obtained was only about 215 000 km/s. Today, when the two quantities have been measured by far more accurately, we would obtain about 300 000 km/s by this method.

Roemer's measurements were accepted with a great deal of scepticism. At the time the velocity he reported was by far too high to be visualized. His contemporaries were not even impressed when he predicted correctly the delay time of the eclipse for one of the Jovian satellites. It was only after Roemer's death that his results were confirmed. In 1728 the periodic displacements of stars were discovered ("stellar aberration"). This phenomenon could only be explained under the assumption of finiteness of the speed of light, and its value obtained from the measurements was 303 000 km/s.

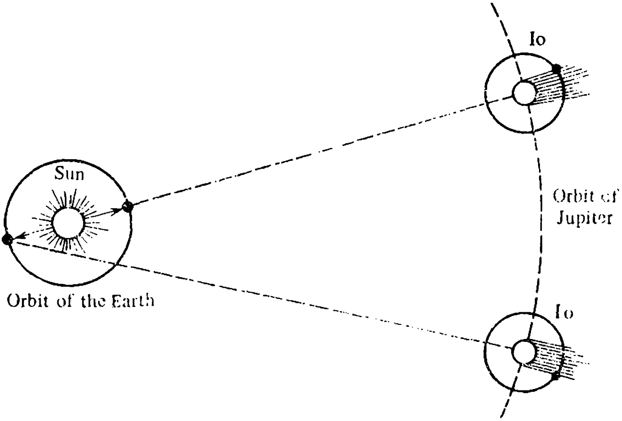


Fig. 26

So far, the measurements of the speed of light had been performed by astronomers. And what about earth-bound laboratories? Could the speed of light be measured in terrestrial conditions? For a long time this was thought impossible.

First "terrestrial" measurements. It was almost two hundred years after Roemer that the speed of light was at last measured in terrestrial conditions. The experiment was performed in 1849 by Fizeau of France and its basic idea was in fact borrowed from Galileo. The difference was that the second observer was replaced by a reflecting mirror and the hand-operated lantern shutter by a rapidly rotating cog-wheel, as shown in Fig. 27. The light from the source S is reflected by the half-silvered mirror O, passes between the cogs of the wheel, reaches the mirror A and, after reflecting, comes back to the wheel W. By

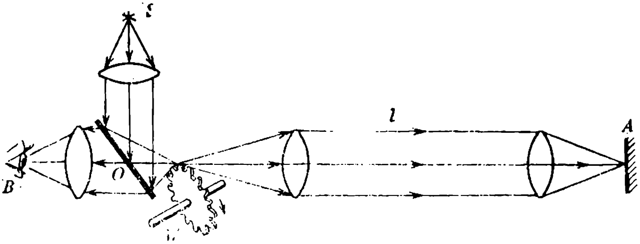


Fig. 27

the moment the light completes its round trip, the gap between the cogs may be replaced by the nearest cog. This means, of course, that the reflected light will be retarded. Alternatively, the wheel turns through such an angle that the light from A is allowed to pass through the neighbouring gap. The observer will then see it. One of the mirrors Fizeau located in Montmarte (Paris, of course), another—in his father's home, 8.66 km away (let this distance be denoted by L). The wheel had 720 cogs and at rotational speed of 25 revolutions per second it provided the maximum intensity of the light ray. The speed of light was then found by Galileo's formula:

$$c = \frac{2L}{t}.$$

Quite obviously, $t = (1/25) \times (1/720)$ s = = (1/18 000) s and

$$c = 312\,000 \text{ km/s}$$

or, with later corrections,

$$c = (299\,870 \pm 50) \text{ km/s}.$$

A modification of the method was proposed in 1868 by Foucault. In his experiment the cogwheel was replaced by a rotating mirror (see

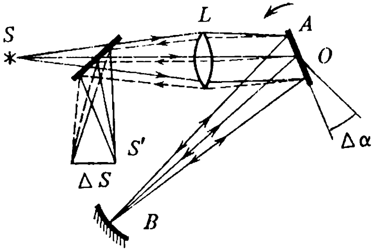


Fig. 28

Fig. 28). If its rotational speed is made high enough, the image of the source S is somewhat displaced for during the time t it takes for the light to go from A to B and back again, the mirror A turns through a certain angle $\Delta\alpha$. If l is the distance between the lens and the image, $l'/2$—the distance between A and B, ω—the angular velocity of the mirror and ΔS—the displacement of the image, then the speed of light is given by

$$c = 4\omega l l'/\Delta S.$$

Foucault's result was $c = 298\,000 \pm 500$ km/s. Further improvements of the method led to the value $c = 299\,810 \pm 50$ km/s. It is interesting to note that in Foucault's experiment the distance l' was substantially reduced, down to 20 meters (from 8.66 km in Fizeau's experiment).

The American scientist Albert Michelson (1852-1931) performed the most accurate measurements of the speed of light. He made use of all advantages of the two previous methods while eliminating their shortcomings. A schematic view of his optical circuit is shown in Fig. 29. A light beam from the source S is reflected by a face of the prism and directed by two flat mirrors K and K' towards the concave mirror A. As a parallel beam it is then transmitted further to the concave mirror B. Being reflected by the mirrors B and B', the light returns to the mirror A and is reflected by it to the flat mirrors d and d' with the resulting formation of an image at the point S'. The angular velocity of the prism can be chosen in such a way that during the round trip of the light the prism turns 1/8 of a revolution. The face b is then replaced by b' and it is the latter that reflects the light beam. Since the speed of light is finite, the image is somewhat displaced. The magnitude of the displacement allows one to calculate the speed of light. In Michelson's

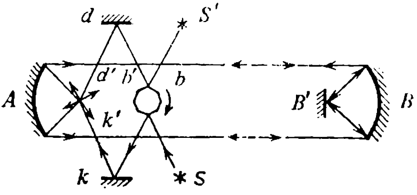


Fig. 29

experiment the result was:

$$c = (299\,796 \pm 4)\ \text{km/s}.$$

All the measurements above were performed in the air. To get the speed of light in vacuum was not much of a problem because the refraction index for the air is well known. The atmospheric inhomogeneity, however, made the results somewhat uncertain, especially at the large distances involved. To overcome the difficulty, Michelson modified his rotating-prism measurements in that the light beam was made to travel in a tube from which all the air had been pumped out. The new result was

$$c = (299\,774 \pm 2)\ \text{km/s}$$

The advances in science and technique allowed some improvements in the old methods and, on the other hand, new methods appeared, based on totally new principles. In 1928, for example, the rotating cog-wheel is replaced by an inertialess electrical light-chopper, which gives

$$c = (299\,788 \pm 20)\ \text{km/s}$$

The coming of radiolocation provided new possibilities and in 1948 Aslaxon obtains $c = (299\,792 \pm 1.4)$ km/s. By using the method of microwave interference Essen finds $c = (299\,792.5 \pm 3)$ km/s. In 1967 the measurements with a helium-neon laser as a source of light give $c = (299\,792.5 \pm 0.5)$ km/s. The methods for measuring the speed of light are continuously improving, but so far physicists have not been able to arrive at the same result. There exists, however, a generally accepted value for the speed of light. According to an international agreement, this is

$$c = (299\,792.5 \pm 0.15) \text{ km/s}.$$

Thus far, in discussing the speed of light, we have been mainly concerned with its magnitude. But there is a by far more serious question to consider: what is, in fact, the physical content of the words "the speed of light"? Everyone knows perfectly well that "speed" is a *relative notion.* We speak of the speed of a sprinter with respect to the spectators on the stands, of the speed of a train with respect to earth, but something goes wrong the moment we come to the speed of light. We are going to say "the speed of light is measured with respect to ..." but here we are forced to stop. With respect to what, indeed? Here again the old problem of ether as a light carrier reasserts itself. Well, the stationary ether is a very convenient absolute frame of reference for all movements. But as we have already seen, its properties are too strange to be visualized, so that the problem is not at all solved.

Still, talking of the ether, one interesting thing is to be noted. It should be realized, namely, that different measurements result, strictly speaking, in different values of the speed of light. How come? In astronomical measurements light always goes from a star or a planet to the Earth so that we may only speak about the speed of light in one direction. In terrestrial experiments we are dealing with light travelling in two opposite directions, for example, back and forth between the mirrors A and B in Fig. 28. What our daily experience tells us is that, generally, the speed of light may be different in these two directions: just remember two boats on a river moving upstream and downstream. But what is here a prototype of the river? The ether, of course. Returning, for example, to the experiment of Fizeau, let us see what are the implications of the existence of the ether. Let us take the AB direction as the direction of the orbital motion of the Earth. Then the velocity of light in this direction (with respect to the stationary ether) will be $c + v$, v being the velocity of the Earth in its orbit, which is about 30 km/s. For the opposite direction BA the velocity of the light ray (again relative to the ether!) will be obviously $c - v$. Does not all this mean that the terrestrial methods give only some average value? But if so, why should we consider the speed of light as a universal physical constant? Well, let us wait and see—the book has not yet ended.

MICHELSON DISAGREES WITH PUSHKIN

A few words about the heading. Isn't this rather a bizarre heading? What could they possibly have in common, the great Russian poet shot in duel in 1837 and the American experimental physicist born fifteen years later? Isn't it just another of the author's tricks? Well, perhaps, but let me continue.

For centuries, the existence of the ether was a matter of common undisputable knowledge. To deny it was every bit as foolish as the assertion that ships could sail without water. It was true that its properties remained a complete mystery and, apart from the mere fact of existence, there was nothing more to say about it. Still everybody believed in the existence of the ether, poets among others. In one of his poems, great Puskhin makes breezy air carry the ether along with it—to convey a vivid picture of a beautiful fragrant Spanish summer night...*

And what about physicists? They tried to use the ether in their what might well be called speculations but, as we have seen, this rather a nonmaterial concept did not represent a fruitful path to follow. First and foremost—the ether firmly refused to manifest itself in physical phenomena.

How shall we detect the ether? By this time in the book, we have seen more than once a remarkable perseverance which is displayed by physicists in solving their problems. To prove the existence of the ether, that was the task the American physicist Michelson took upon himself. (The fact itself was self-evident for him, as well as for all his scientific contemporaries.) Michelson believed that the motion of the Earth around the Sun should produce an apparent motion of the ether, the "ether wind", much as a moving train causes an apparent air wind, even though the air itself is at rest (with respect to earth, should be added). But if the ether wind actually blows, its effect on the speed of light will depend on the angle between the light ray and the direction of the Earth's motion. It will be more pronounced, of course, if the angle is a right one. Clearly, if there is no ether, the direction of light is immaterial.

It is hard to exaggerate experimental difficulties Michelson had to overcome in constructing his "ether wind" apparatus. What he was going to detect was the effect of the Earth's motion on the speed of light. The speed of the Earth (30 km/s) being a mere one-ten thousandth of the speed of light, there was no much to expect and the apparatus was therefore supposed to show all the accuracy imaginable, and even more. But—no one at the time could exceed Michelson in the art of experimentation. The scheme of his apparatus is shown in Fig. 30. The light ray from the source S falls on the half-transparent plate O, which is inclined to the direction of the ray by 45°. The ray is split by the plate into two rays at right angles to one another. Having been reflected by the mirrors M and M' both rays come back to O, where they are split once again. One part of each of them goes towards A, where their interference is observed. The interference pattern is determined by an optical path difference of the two of them. If the lengths OM and OM' are equal, the difference can only result from the fact that, due to the effect of the ether, the light speed is different in these two respective directions.

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* The translator has no courage to tamper with the lines quoted in the original for fear of spoiling their music.

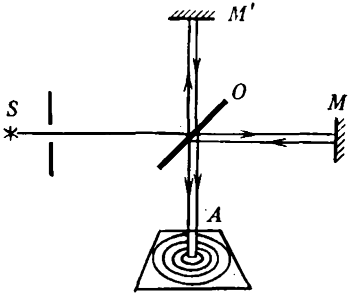

Fig. 30

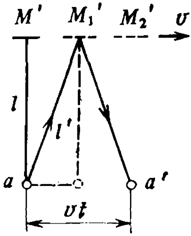

Fig .31

Let the path OM be aligned in the direction of the Earth's orbital motion. Then, the time it takes for the light beam to travel OM back and forth is

$$t_1 = \frac{l}{c+v} + \frac{l}{c-v} = \frac{2l}{c}\,\frac{1}{1-\frac{v^2}{c^2}},$$

where v is the velocity of the Earth in ether.

For the second light beam, travelling from O to M and back again (which is normal to the Earth's motion) one has to take into account the "ether-river" drift (see Fig. 31). The addition of the velocities involved gives us the effective light speed equal to $\sqrt{c^2 - v^2}$ and the time required for the round trip is

$$t_2 = \frac{2l}{c}\,\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}.$$

Thus, the difference in the times of light propagation over these two paths is

$$\Delta t = t_2 - t_1 = \frac{2l}{c}\left(\frac{1}{\sqrt{1-\beta^2}} - \frac{1}{1-\beta^2}\right),$$

where $\beta = v/c$.

Taking into account that $\beta = v/c$ is very small, we obtain

$$\Delta t \approx -\frac{l\beta^2}{c}.$$

If all the setup is rotated through 90 degrees, the difference in the times will be $2\Delta t$. The path difference for the light beams which corresponds to a time difference of $2\Delta t$ is $2c\Delta t$. The interference fringe shift corresponding to such a path difference is then

$$\Delta N = \frac{2c\Delta t}{\lambda} = \frac{2l\beta^2}{\lambda},$$

where λ is the wavelength of the light. In Michelson's experiment an anticipated fringe shift was $\Delta N \simeq 0.4$, that is some 20 to 40 times larger than the experimental error.

Even though Michelson's experiment was repeated many times and in various conditions, *the measured fringe shift was invariably zero.* The first and most natural conclusion to come into mind was, of course, that there is no such a thing as ether and, accordingly, there is no preferential frame of reference attached to it. Still, the physicists were too much under the influence of the ether to give up the idea, and several desperate attempts were undertaken to save it.

In 1892, the Irish physicist George Fitzgerald proposed an idea that all bodies contract in the direction of their motion in such a way as to compensate for the time difference due to the difference in velocities of light parallel and normal to motion. This was a good explanation for the null result of the Michelson experiment but the question was why should there be such a contraction. In 1895 H. Lorentz proposed a tentative explanation for it. Substance consists of molecules held together by electromagnetic forces. When these molecules take part in motion these forces would change in such a way as to produce the Fitzgerald contraction. But then the effect could depend also on the chemical composition of the moving body. However the Michelson experiment with different materials showed no sign of such dependence.

Some scientists believed, further, that the ether could be wholly carried along by the Earth's atmosphere. A thorough analysis showed, however, that this hypothesis didn't agree with the observations of the motion of stars. Nor did it agree with the experiments performed by Fizeau back in 1851, when he was studying the light carried along by moving water. What he found was that the hypothetical ether was partly carried along by a moving substance and just how large the carried along part was depended on the refraction index of the substance. If the index is unity, the light is not carried along at all but this is very nearly the case with the Earth's atmosphere.

Still another ether-saving idea was that the speed of light in the ether depends on the speed of the source of light. Observations of stars have not, however, supported this idea. In 1956, in particular, Soviet physicists A. M. Bonch-Bruevich and A. P. Molchanov found that, in spite of the Sun's rotation, the velocity of the light coming from various edges of the Sun's disk is always the same.

Bearing in mind that every experiment has its accuracy, what Michelson's experiment actually established was that the speed of the "ether wind" could not exceed 5-7 km/s. Illingworth improves the measurement techniques and lowers in 1927 this limit to 1 km/s. Picard and Stael, of France, use an air balloon to lift Michelson's interferometer high into the atmosphere—no ether there. Essen employs the interference of standing electromagnetic waves to show that the ether wind cannot be faster than 0.24 km/s. In 1958, using laser techniques, C. Townes goes down to 1/30 km/s, to be followed by Champney with coworkers who obtained 5 m/s. And finally in 1964 the same Townes leaves only 1 m/s as the maximum possible speed of the ether wind. Since 1881 up to now the upper limit for the speed of the ether wind has been lowered down by a factor of 5000! Today, we can say with firm conviction that the ether does not exist.

The importance of this conclusion for science is demonstrated clearly enough by the very list of the experiments mentioned. It was now shown beyond any doubt that there is no such thing as the motion with respect to the stationary ether. There is no medium that could be used as the absolute frame of reference. The hypothesis of ether becomes unacceptable, it disagrees with experimental facts. The Michelson experiment shows that *the speed of light in vacuum is the same for all frames of reference, however their motions might be.* Now (and only now) we state without any reservations that *the speed of light in vacuum is a universal physical constant.*

Well, by united efforts of physicists, the ghost of ether was at last banished from science. Michelson was right: the ether had nothing to do with light nor with nights of Spain. But can we help admiring the daring poetry of great Pushkin?

THE WORLD OF ALBERT EINSTEIN

More than once in this book we have quoted Newton: "There is not a sufficient number of experiments." As you may remember, this was the reason why Newton was unwilling—or, indeed, unable—to say anything definite about ether. For nearly two centuries after Newton, the "number of experiments" increased immensely, physicists acquired a deeper insight into the essence of natural phenomena, but the situation with ether had not in fact changed. And yet—there was the Michelson experiment! In spite of its negative result, it was a real shock for scientists. They were too accustomed to the idea of ether and even though they could not actually employ it, as it were, explicitly, ether lay in the foundation of their world view. And now the foundation was tottering. The Michelson experiment brushed aside the idea of ether. But then what remained there instead? What new foundation was there to build on? It was great Albert Einstein who answered this question. Let me quote here from Max Planck: "An experimenter is a person that stands on the front line, that performs decisive experiments and measurements. An experiment is the formulation of a question to be asked of Nature, while the measurement is the acceptance of the answer given by Nature. But, before the experiment is set up, it should be thought over, or, in other words, one should formulate the question to Nature; before the measurement is estimated, it should be interpreted, or, in other words, one should understand the answer given by Nature. These two problems are for a theoretician to deal with." From the point of view of the logic of science, it was the Michelson experiment that led to Einstein's epochal discoveries. Let us now try to get an idea of what it was that Einstein contributed to modern scientific thought. To do this, it will pay to discuss the matter from a somewhat different angle.

It was already known to Galileo that all physical phenomena proceed identically in the systems which move with respect to each other uniformly and in straight lines (i.e. in "*inertial*" *systems*). Our experience tells us that this principle is always at work. If yesterday the passengers of the steamboat had lunch on the shore and today they prefer their cabin, nothing shows them that they are moving. If one of them is somewhat clumsy, his sandwich will fall in the same deploring plumb-line way as it did yesterday. It is

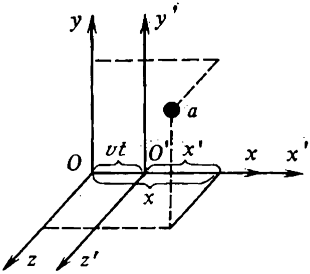

Fig. 32

only through a sharp jerk or slowing down that the passengers are reminded about their motion with respect to the shores. This principle, according to which all physical laws are the same for all observers moving with a constant speed, has come to be known as *Galileo's relativity principle*. The coordinates and time in a stationary frame of reference (say, shore) are very simply related to the coordinates and time in a moving frame (see Fig. 32):

$$x' = x - vt;\ y' = y;\ z' = z;\ t' = t.$$

(Here the primed quantities are those for the moving frame of reference, v being its velocity relative to the stationary one.) What is to be noted about these equations, is that time remains totally unaffected by motion (it is the same in both systems or, as physicists say, time is absolute). The dimensions of a body are also independent of whether it is at rest or moving (length is absolute). Having been introduced by Newton, absolute space and time for about two centuries remained unquestionable fundamentals of his mechanics.

And what about electromagnetism? Well, the electromagnetic phenomena are different in reference systems moving with respect to each other. Let an electric charge Q be at rest in the right system in Fig. 33. By the laws of electrostatics, it establishes an electrostatic field around itself, only this and nothing more. Not so, however, for an observer in the left frame of reference which moves with respect to the first at a velocity v. For him, the charge is in motion and may (and should) be considered therefore as an electric current. But an electric current always produces a magnetic field. We thus end up with

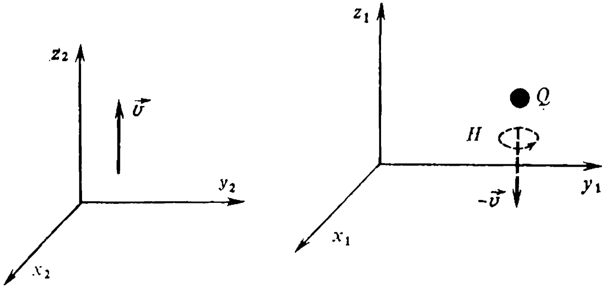

Fig. 33

different fields in different frames of reference which is a clear violation of Galileo's principle.

The speed of light shows another example of misconduct with respect to this principle. Indeed, if its value is c in one system, in another it should be c plus (or minus) v (v being their relative velocity). But this contradicts with the experimental facts (Michelson) as well as Maxwell's electromagnetic theory, in which the propagation speed of electromagnetic oscillations is always c, whatever the motion of a system.

The disagreement between the relativity principle and electromagnetic phenomena puzzled scientists for a long time. In trying to solve the problem, various but short-lived theories were proposed.

Attempts were made, for example, to limit the validity of the relativity principle: it works in mechanics but does not apply to electrodynamics. But then, for logic to be satisfied, the laws of electrodynamics should be correct in only one privileged frame of reference, where light propagates with the velocity c. This reference system could only be ether, already discredited.

Another approach was to reformulate Maxwell's equations in such a way that, in going from one inertial system to another, they should remain unchanged. This also implied the existence of ether: it should be wholly carried along by bodies, again in contradiction to observations.

All attempts of this kind were based on classical Newtonian notions of absolute space and time. It was the basis itself that was to be replaced.

Einstein's theory of relativity. The solution proposed by Einstein appears to be very simple:

both the relativity principle and the laws of electrodynamics are valid. This proposition was expressed by Einstein in his first postulate: all natural phenomena proceed identically in all inertial frames of reference. His second postulate stated that the speed of light in a vacuum is the same in all inertial frames of reference ("the constancy principle").

The problem to be solved in the first place was to find out what transformations of Maxwell's equations could leave the speed of light unchanged in going from one reference system to another. The needed transformations turned out to be:

$$x' = \frac{x - vt}{\sqrt{1 - \frac{x^2}{c^2}}}; \quad y' = y; \quad z' = z; \quad t' = \frac{t - \frac{vx}{c^2}}{\sqrt{1 - \frac{v^2}{c^2}}}. \tag{6}$$

As a matter of fact, these transformations had already been obtained earlier—by Lorentz. What makes all the difference in the world, however, is the way in which Einstein rederived them. Here is what Hermann Minkowski says about it: "(Lorentz) found them ... as an hypothesis of the contraction of bodies in the process of their motion. Einstein showed that in the postulate of relativity we are dealing not only with the contraction hypothesis, but with the new treatment of time as well." *Time—the only, true and absolute, tacitly assumed to be the same always and everywhere—this time turns out now to run differently in different reference systems.* This was, of course, a break with classical notions and its implications were often too paradoxical to be easily accepted. Still, experiment, the High Court of Appeal in science, never failed to confirm them.

The lack of space makes it impossible to discuss here in any detail the numerous consequences of Einstein's theory. There are a great many excellent books on the subject (popular among them) which we can recommend to our reader. Let us see, however, what new things we can learn from the relativity theory about the speed of light.

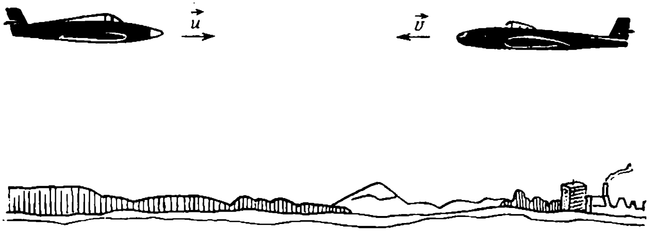

Fig. 34

Addition of velocities. The Lorentz transformations (6) may be used to work out the transformation of velocities in going from one reference frame to another. Let us look at the following example.

Two aircrafts are moving in opposite directions, one having the velocity u and another v with respect to the Earth (see Fig. 34). As Newtonian mechanics teaches us, their absolute relative velocity $\tilde{u}$ is

$$\tilde{u} = u + v. \tag{7}$$

Let us now obtain a relativistic version of this equation. To this aim, we shall use, of course, the Lorentz transformations (6), considering, say, the Earth as the stationary frame of reference and the left plane as the "primed" one (which moves with a velocity v relative to earth). What is the velocity of the right plane in the primed frame? We find

$$v' = \frac{x'}{t'} = \frac{x - ut}{t - \frac{ux}{c^2}} = \frac{\frac{x}{t} - u}{1 - \frac{u}{c^2}\frac{x}{t}}.$$

Since the right plane is moving to the left, we have $v = -x/t$, so that, finally, we have, taking modulus:

$$v' = \frac{u + v}{1 + \frac{uv}{c^2}}. \qquad (8)$$

A very important feature of this equation is to be noted. If the right plane is moving with respect to earth with a speed c, it follows immediately that, like it or not, its velocity with respect to the left one is also c:

$$v' = c.$$

A plane cannot, of course, fly with the speed of light—light can. So, light has the same speed from the point of view of any observer, whatever his own velocity. This explains why Michelson's experiment gave null result—without ether even being mentioned.

The correspondence principle. Another interesting feature of equation (8) is that at ordinary velocities (much lower than that of light) it leads to the classical formula (7). Indeed, taking $v \ll c$ and $u \ll c$, we can ignore the term uv/c^2 in the denominator, which gives immediately $v' = u + v$. We thus see that Einstein's theory of relativity does not repeal the laws of Newtonian mechanics but strictly defines the domain of its validity. From the point of view of the evolution of science, this is a conclusion of paramount importance. Indeed, any new physical theory (if it is correct) is supposed to include all the results of the old theory and the validity area of the old theory should, of course, be clearly indicated. This is the so-called *correspondence principle*. We shall encounter it again in our next Story.

Velocity dependence of mass. Here is another impressive result of the relativity theory. The reader must be familiar with the law of conservation of momentum in its simplest form:

$$M_1v_1 + M_2v_2 = \text{constant} \tag{9}$$

(recall that the momentum of a body is the product of its mass M and its velocity v). In relativistic mechanics, the same law will be

$$\frac{(M_1)_0 v_1}{\sqrt{1-\left(\frac{v_1}{c}\right)^2}} + \frac{(M_2)_0 v_2}{\sqrt{1-\left(\frac{v_2}{c}\right)^2}} = \text{const}, \tag{10}$$

where $(M_1)_0$ and $(M_2)_0$ are the masses of the two bodies. For a true Newtonian these masses (and all others, for that matter) are, of course, constant and independent of velocity. But equation (10) may be rewritten in the usual form (9) if one assumes that mass and (its) velocity are related by

$$M = \frac{M_0}{\sqrt{1-\frac{v^2}{c^2}}}, \tag{11}$$

where M_0 is the mass of the body at rest. What actually happens is that one is *forced* to write this expression. Its rigorous derivation is somewhat lengthy to be discussed here, but, once written, the formula immediately explains the measured dependence of the electron's mass on its velocity (shown back in Fig. 18). It may also be seen that, at velocities $v \ll c$ (when v^2/c^2 may be dropped) the equation takes its familiar form:

$$M = M_0 = \text{constant.}$$

This is just the reason why the mass of a body had been considered for centuries as its inherent and invariable property. It was with the advent of the electron at the end of the nineteenth century, that the situation changed. Its extremely small rest mass (9.1×10^{-28} g, in case it slipped your mind) gave scientists an opportunity to observe velocities close to that of light. The change of mass with velocity was one of the first relativistic effects to be observed.

A new form of Newton's second law. Since the mass of a body turns out to depend on its velocity, Newton's second law is to be modified. In its usual form, $\vec{a} = \vec{F}/m$, it contains nothing to limit velocity. If a body is accelerated long enough by the application of force, however small, it must eventually reach the speed of light and even exceed it. Einstein rewrites the second law of dynamics:

$$\frac{d(m\vec{v})}{dt} = \vec{F} \qquad (12)$$

(which is, surprisingly enough, just the form Newton used himself). For velocities much lower than c, m is constant, so that Einstein's law coincides with the law of Newton in its usual form. We thus have arrived at another illustration of the correspondence principle: a new theory includes old notions, indicates the limits of their validity and enlarges our scientific knowledge.

A very important result can be obtained from equation (12). As the speed of an object approaches that of light, its mass becomes so large that any further acceleration becomes all but impossible. If, for example, an electron acquires a speed of 0.99999992 times c, its mass increases by a factor of 2500. For further acceleration, then, much larger forces are needed—but the mass increases in turn and, however long the force is applied, the velocity remains essentially the same. It follows that the speed of light is the maximum possible in Nature: a material object cannot overtake a light ray.

The speed of light and energy. Still another fundamental consequence of the relativity theory is the relationship between mass and energy which is, in fact, a cornerstone of nuclear and elementary particle physics (as we shall see in detail in Sixth Story). Let us see where it comes from—to show once more the speed of light at work.

An increase in speed is accompanied, as we have already seen, by an increase in mass. But the change in the speed of a body is associated with the change in its kinetic energy $E_k = (mv^2)/2$. Does not this mean that its mass and energy are somehow interrelated?

Well, it does. Let us rewrite equation (11) in the low-velocity approximation:

$$M \approx M_0 \left(1 + \frac{1}{2} \frac{v^2}{c^2}\right).$$

It may be seen from the expression that the increase in the kinetic energy of a body by the quantity $(M_0v^2)/2$ changes its mass by

$$\Delta m = \frac{M_0v^2}{2c^2} = \frac{E_K}{c^2} .$$

This relationship was vastly generalized by Einstein. He showed rigorously that the energy of any physical body may be represented as

$$E = Mc^2 = \frac{M_0c^2}{\sqrt{1-\frac{v^2}{c^2}}} .$$

At low velocities this equation may be approximated by

$$E \approx M_0c^2 + \frac{M_0v^2}{2} .$$

The second term in this formula is the usual kinetic energy, the first determines the energy of the body at zero velocity. This is the so-called *rest energy*, introduced by Einstein:

$$E_0 = M_0c^2. \qquad (13)$$

Isn't this a remarkable result? The mere fact that a material body has mass endows it with energy, mc^2. To give an example, one gram of any substance has a rest energy of 9×10^{13} J which is much more than the usual energy released in the process of burning. For comparison, one gram of coal, when burnt, gives off only 3×10^4 J, just a tiny fraction of its rest energy. The law of conservation of energy has acquired a new content: it has become the *unified law of conservation of mass-energy*.

The mass of light. Let us return for a while to the second section of this Story. In discussing the photoeffect, we were obliged to ascribe some particle properties to light. We (Einstein rather) assumed that the energy of a photon is

$$E = h\nu.$$

But, according to Einstein, a photon is also endowed with a mass m_{ph}:

$$E = h\nu = m_{\text{ph}}c^2; \quad m_{\text{ph}} = \frac{h\nu}{c^2}.$$

This mass is extremely small, of course, about 10^{-33} g, but some way or another, it is bound to manifest itself in physical phenomena. Indeed, in 1900, P. N. Lebedev, Professor at the University of Moscow, discovered the pressure of light, which was an experimental proof of the then still unformulated relativity theory. Another evidence for the photon's mass came much later, in 1919, when in full agreement with Einstein's prediction, scientists registered the bent of light rays in the strong gravitational field of the Sun. But this is the theme of our next section, for certainly it deserves a special discussion.

SPACE FULL OF LIFE

When flooded with congratulations for the Nobel Prize, Einstein once said: "Why so many words? I didn't digress in my work, that is all." Well, one suspects things are not as simple as that, but what is indeed amazing was Einstein's capacity to focus his powers on a single problem until he was able to achieve the utmost lucidity possible. No sooner had he accomplished the series of works on the relativity theory than another, still more profound problem called his attention. This was gravitation. Now that the relativity theory had been formulated, it was clear that, in spite of all its successes, the Newtonian gravitational theory was incomplete. We know, indeed, that no interaction can propagate at speeds exceeding that of light. But this our knowledge is nowhere reflected in Newton's formula

$$F = G\frac{M_1 M_2}{r^2}.$$

According to this law, the change in the position of the first body causes an immediate change in the force acting on the second one. Which means, in fact, that we are dealing with an interaction that propagates with an *infinite* speed.

The method employed by Einstein for solving the problem of gravitation was basically the same he used in the relativity theory. To satisfy both mechanics and electromagnetism, he had extended Galileo's relativity principle to include electromagnetic phenomena. To cope with infinitely fast interactions in Newton's theory, Einstein was moved to bound the "constancy principle" by the regions with negligible gravitational forces. Since all bodies, when subjected to gravitational forces, are accelerated, a general approach was to be found to describe the motion of bodies in accelerated frames of reference (i.e. in *non-inertial* frames).

How many masses in a body? "Only one, of course," the reader may say, "which is the measure of its inertia". Well, not quite. Einstein, at least, was not the man to be satisfied by this answer. He brought to light a very fundamental fact known from Newton's time but ignored owing to its apparent self-evidence.

The reader may have noticed that the term "mass" has been in fact used in our book in two senses. On the one hand, we have used the "*inertial*" *mass* m_{in}, a quantity which measures a response of a body to a given force according to Newton's law $F = ma$. This mass can be measured in experiments which have nothing to do with gravity. On the other hand, there is the "*gravitational*" *mass* m_{gr}. This is the measure of the specifically gravitational attraction of two bodies. It is not evident a priori that these two quantities are the same. Strictly speaking, Newton introduced into physics two different masses not pertaining to each other. Perhaps these two masses are entirely different physical concepts? Be it as it may, every body is characterized by definite values of m_{in} and m_{gr} and some relationship between them should reasonably be expected. Can this relationship be determined by the chemical composition of a body? It is extremely undesirable, for physical equations would then be too complicated. Well, the answer came from utterly different quarters. Mass, time and length are the fundamental physical properties of our world, and in solving the problem of mass we are dealing with the most profound characteristics of the Universe.

The principle of equivalence. Newton was the first to try to find a relationship between m_{in} and m_{gr}. Experimenting with a number of pendula, all of the same length but with the loads of different weights, he discovered that the period of oscillations did not depend on the $m_{\text{in}}/m_{\text{gr}}$ ratio. From this he concluded that, to within 0.01%, inertial and gravitational masses are directly proportional to one another:

$$m_{\text{in}}/m_{\text{gr}} = \text{const.}$$

This relationship was later confirmed by many people. In experiments by Roland von Eötvös (in 1890) and, in more recent time, by Robert H. Dicke at Princeton University and V. B. Braginskii (USSR), the accuracy in determining $m_{\mathrm{in}}/m_{\mathrm{gr}}$ was about one part in 10^{12}. This means that m_{in} and m_{gr} are actually equal. This fact has come to be known as the *principle of equivalence.*

Taking together the inertial and gravitational properties of physical bodies, this principle links the law of universal gravitation and the second law of dynamics. Einstein recognized all the significance of the principle of equivalence and made it a basis of his gravitation theory. For him, gravitation and inertia are essentially the same phenomenon. This is no longer the property of a body itself but rather an intrinsic *property of the space* containing the body.

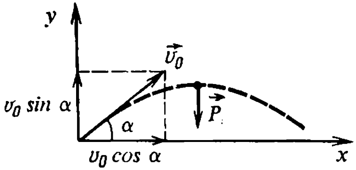

Fig. 35

If properly interpreted, a well-known textbook problem may be used to illustrate this idea, namely, the motion of a body thrown at an angle to the horizon (see Fig. 35). In horizontal direction we have a uniform motion described by the equation

$$x = v_0 \cos \alpha t,$$

where v_0 is the initial speed of the body, α the angle of throwing, t the time. Vertically, the body moves against the force of gravity and is therefore uniformly slowed down. The law of this motion is:

$$y = v_0 \sin \alpha t - \frac{g_0 t^2}{2}.$$

Let us eliminate t between the equations. This leaves us with the equation for the path of the body's motion:

$$y = x \tan \alpha + \frac{g_0}{2v_0^2 \cos \alpha} x^2.$$

Looking into this formula we can see that the initial conditions of the motion (the velocity v_0 and the angle α) are at the experimenter's will and can be varied arbitrarily. This equation shows us that the *trajectory of a body is independent of mass.* In a given gravitational field, all bodies, light and heavy alike, move along the same paths (provided, of course, the initial conditions are the same). The characteristic of this field is g_0, the free fall acceleration. The path of a body is determined solely by the properties of the field itself, that is, by the *gravitational properties of the space.* What is, in fact, the essence of Einstein's new view is that there is a hitherto unsuspected connection between the geometry of space-time and gravitation. Or, in other words, the presence of gravitational mass changes geometrical properties of space and time. The theory of relativity we have thus far described is only concerned with "inertial" frames of reference—this is why it is called *"special" theory of relativity.* His *"general" theory of relativity* includes accelerated systems as well. The special theory still left place for ether in the area of accelerated motions. Now, in the general theory, ether was eliminated from physics once and for all.

A simple experiment may be helpful to illustrate (in inevitably oversimplified manner) how the presence of mass may change the properties of space. Let us put a heavy ball on a flat rubber sheet stretched over a frame. As shown in Fig. 36, the ball will flex the sheet, producing a depression. Now if another, smaller and lighter ball is put on the sheet (our analog of space) and is set into motion, what its path will be? Clearly, it depends on how far from the heavy ball it moves. If it is far enough, the light ball will go unhindered (Fig. 36,a). Otherwise its path may be bent (Fig. 36,b) or even, the small ball trapped

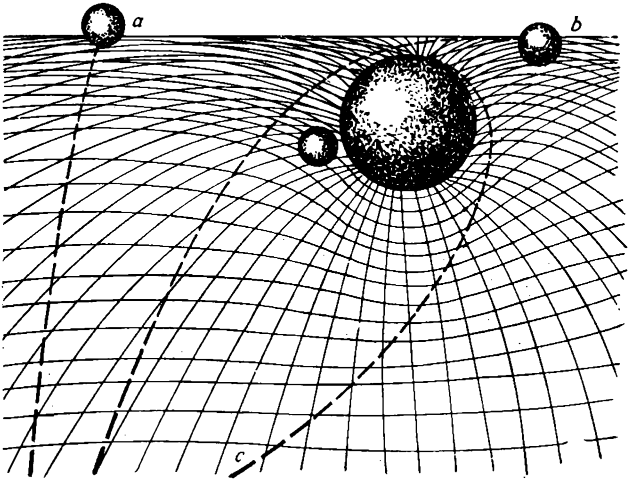

Fig. 36

into the depression, may perform several revolutions around the heavy one and fall on it (Fig. 36,c).

To draw such a simple rubber-sheet picture in the real "curved" three-dimensional space is a little bit too much for our imagination. We are told that Einstein was once asked by his son: "Daddy, why are you such a celebrity?". The Daddy laughed and then answered seriously: "You see, when a blind bug crawls along the surface of a ball, it does not notice its path to be bent. I'am lucky enough to have noticed it". Still, it is not the accessibility (or shall we say "visualizability") of a theory what really matters. The success (or otherwise) of a theory depends upon whether or not its predictions are in agreement with observations. In this sense, the general theory of relativity was a real triumph. Two most spectacular confirmations of its validity were the explanation of Mercury's perihelion motion and the bending of light by the Sun.

You may remember from the first Story that the perihelion of Mercury has a very slow (but measurable) motion that remained a complete mystery for Newtonian mechanics. The equations of Einstein's theory of gravitation explained this motion in very good agreement with observations. It should be noted that Mercury is the nearest to the Sun planet (very close, so to speak, to the large ball of our rubber-sheet model). No wonder, then, that it is most influenced by the "curvature" of space due to the gigantic mass of the Sun.

Another great success of Einstein's theory was the bending of light rays in the gravitational field of the Sun, an effect predicted by Einstein and confirmed by astronomers. We have already seen that the particles of light are endowed with some mass. Hence, they have to be attracted by the Sun or, to put it another way, in the vicinity of the Sun the trajectory of light is to be deflected. One obvious consequence of this is the displacement of the apparent positions of stars (see Fig. 37). In 1919, a small area of the sky was photographed twice: during the eclipse of the Sun and some time before, when the Sun was out of the way. In the latter case, the gravitational field of the Sun played no role, while in the former it was assumed to bend light rays coming from the stars. The positions of the stars on the two photographs turned out to be different. One cannot but agree with Planck in that the idea of an experiment should be proposed by a theoretician!

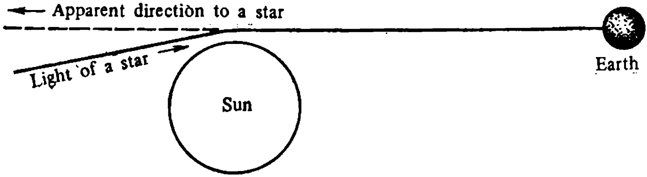

Fig. 37

For an unprepared reader the contents of this section may at times have seemed rather heavy going. Hardly surprising. But, to give you some amount of optimism, let me quote here our sci-fi writers, the Strugatskii brothers: "... in a dozen years or so, any schoolboy will be more at home in the general relativity theory than a present-day specialist. This is not to say that one has to understand precisely how the curving of space-time really occurs. It is only needed that every one should become familiar with these ideas from childhood. They should become a part of our everyday life".

Isn't it a remarkable physical constant, the speed of light? We have seen on the pages of this Story that many scientific discoveries were associated with it. The solution of the problem of light led to convergence of various branches of physics such as mechanics, electrodynamics and optics, thus presenting another manifestation of the Unity of the World. Here are the words of Einstein, the creator of new physics: "It is so beautiful to find unity in the complex of phenomena that at first sight appeared to have nothing in common".

FIFTH STORY

Mysterious Messenger from Real World or the Tale of Planck's Constant

AD HOC HYPOTHESIS (THE EMERGENCE OF PLANCK'S CONSTANT)

Unlike many other universal physical constants, Planck's constant has a definite birthday, December the 19th, 1900. This day, at a regular session of the German Physical Society, Max Planck made a report in which, to explain black-body radiation, he introduced a new quantity h. On the basis of experimental data, Planck had found its value to be

$$h = 6.62 \times 10^{-34}\ \mathrm{J \cdot s}.$$

As you know, bodies irradiate energy—either in its invisible form, as a central-heating radiator, or in the form of the mild glow of an electric-stove spiral. Or it may be the blinding light from the incandescent filament of an electric lamp. The Earth receives the radiation, both light and thermal, coming from the Sun, in whose interior the temperature reaches millions of degrees. It is also well known, on the other hand, that bodies vary in their ability to absorb light. The window glass transmits light freely, but draw the curtain and it becomes darker in the room because the light is absorbed by cloth. A body which is a good light-absorber appears black (sooth, for example). But if you are a mountaineer, you no doubt use your sunglasses to stand the blinding radiance of snows there on the heights: snow is good to reflect light. Certainly, the problem of absorption and radiation did not fail to receive attention by physicists but, as we shall see shortly, it turned out a hard nut to crack.

Perfectly black body. In 1859 the German physicist Gustav Kirchhoff, one of the first to probe into these matters, stated the rule: if a physical system is in thermal equilibrium, the energy it absorbs equals the energy it gives away in the form of radiation. Sounds very seriously but, as a matter of fact, all of us know this rule very well and often use it in our daily life without giving it too much thought. To dry his wet sneackers, no tourist will throw them into the bonfire. Rather, he places them prudently at a distance where the heat (or the thermal energy, if you will) is weaker. The balance between the absorbed and radiated thermal energy secures the temperature just required for safe drying. When expressed mathematically, Kirchhoff's law has the form:

$$\frac{E(\nu,\ T)}{A(\nu,\ T)} = \varepsilon(\nu,\ T),$$

where $E(\nu, T)$ and $A(\nu, T)$ are, respectively, the emissive and absorptive power of the body, ν is the frequency of radiation, T the temperature and $\varepsilon(\nu, T)$ is some universal function (later to be discussed).

Kirchhoff introduced into science the concept of perfectly black body. This is a body that absorbs all the incident energy, no matter what the radiation frequency. For such a body, evidently,

$$A(\nu, T) = 1.$$

No such body really exists, but we can conceive of a model that represents it pretty well. Take a box whose inner walls are made of a good reflecting material. Now make a small hole in the box.

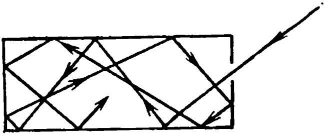

Fig. 38

When a ray enters the box, it is reflected many times by the walls and does not find its way out, i.e. it is absorbed (see Fig. 38). By the way, your room is also sometimes a black body (if not perfect): you remember, of course, that windows in day-time appear rather dark from outside. The reason is very nearly the same: the light entering the room cannot leave it and a man in the street cannot see, therefore, what is going on inside.

For a perfectly black body $A(\nu, T) = 1$, so that the physical meaning of the function $\varepsilon(\nu, T)$ becomes quite clear: it is nothing other than the emissive power of a perfectly black body. To find the explicit form of $\varepsilon(\nu, T)$ would be extremely desirable and important: this is a function which is the same for all bodies, a so-called universal function. Physicists are fond of universal functions.

Ultraviolet catastrophe. A method to determine $\varepsilon(\nu, T)$ experimentally was proposed by Kirchhoff. The idea was to use the "black box" we have just described. The radiation coming from the hole was decomposed. It was rather a difficult task, but in early 20th century the form of $\varepsilon(\nu, T)$ was already known (see Fig. 39). And, of course, it had to be described theoretically.

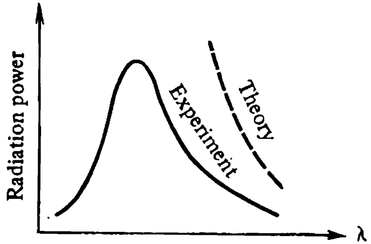

Fig. 39

It was at this stage that troubles began, of the most fundamental nature as it later turned out. Looking backwards we can now see distinctly what was the major stumbling block. Even though the electron had already been discovered, there were no data whatsoever as to the inner structure of the atom. The fundamental ideas needed for solving the problem were yet to come.

The generally accepted picture of what is happening in a black body cavity was in outline as follows. A body is made up of charged particles whose oscillations produce electromagnetic radiation. This radiation is, in fact, a set of electromagnetic standing waves occurring in the cavity.

Their wavelengths are $\lambda_n = 2l/n$, where $n = 1, 2, 3$, etc. The longest possible wavelength is, evidently, l, the size of the box which we take as a model of a black body. Note that a wavelength may be arbitrarily small.

According to Boltzmann's principle of equipartition of energy (see Third Story), the whole of a body's energy is divided equally between the standing waves. On the other hand, as we have just seen, the vast majority of them have short wavelengths, with an immediate conclusion that black body radiation should be most intense in the ultraviolet region (see Fig. 39, the dashed line). But every one knows that the spiral of an electric stove glows dull red. That was a more serious contradiction than it may seem at first sight. That was, in fact, a bankruptcy of classical physics and its principles, the so-called ultraviolet catastrophe.

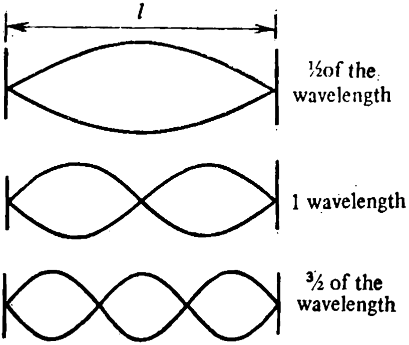

Fig. 40

Such was the state of affairs when Max Planck (1858-1947) came to the stage. His approach to the problem was totally different. "Facts,— he once wrote,—are the Archimedes' lever that moves the most solid theories!". If there is no theory to describe the experimental curve, let us try it another way. We can find (or guess at) an empiric ("ad hoc") formula capable of describing the curve and then think it over and justify it theoretically. We frankly admit that such an approach has little to do with Science (with capital S) but what else is there to do?

Well, Planck did find—indeed, invented—a formula that perfectly fitted all of the experimental data, but it was when he tried to derive it that the real story began. Eventually, he was forced to take most radical steps tantamount to descrediting the very fundamentals of classical physics.

A hint by Boltzmann. Planck's first attempts in this direction were invariably futile. An interesting fact seems to be worth mentioning here. In his book "On the Paths of Science", the distinguished French physicist Louis de Broglie writes that when Planck told Ludwig Boltzmann about his failures, the latter noted that the true theory of radiation cannot be constructed without inserting a (previously unknown) element of discreteness.

It was this idea, substantiated by Planck, that pushed the problem forward. Planck assumed that *atoms could change energy, when they emitted and absorbed the radiation, only in quantized units that he called quanta.* The energy E of such a quantum and its frequency ν are related by

$$E = h\nu,$$

where h is the new constant Planck introduced in December 1900. Later, when its physical significance became clearer, it was called *Planck's constant* and as such it enters our Table of universal physical constants.

With discreteness thus introduced into radiation processes Planck succeeded in deriving his hitherto purely empiric formula. Using the constant h, he was able, further, to evaluate the most important universal constants, such as Boltzmann's constant k, Avogadro's number N_A and the electron charge e. All expectations seemed to be surpassed but now a final and most dramatic period begins, that of interpretation of the formula and of the underlying assumptions.

What Planck perfectly realized was that his quantum hypothesis was completely alien to the whole of the nineteenth-century physics. All his efforts to introduce h into classical electrodynamics ended in nothing. He wrote: "The frustration of all the attempts to bridge the abyss soon eliminated all doubts possible: either the quantum of action h was a fictitious quantity (then all the derivation of the law of radiation was in principle illusory and was nothing more than an empty game of formulae) or in the process of the derivation some sensible physical idea was used as a basis. Then the quantum of action must play a fundamental part in physics, its emergence announced something absolutely new, thus far never heard of, something that seemed to require transformation of the very foundations of our way of thinking which, since Newton and Leibnitz had founded calculus, was based on the assumption of the continuity of all causal relationships." The old question of the nature of light was raised again. For Planck, radiation and absorption were discrete, discontinuous processes; for Maxwell, light propagated continuously. Planck wrote, diffident and full of doubts: "Bearing in mind the full experimental confirmation of Maxwell's electrodynamics in investigating even the most complicated phenomena; bearing in mind the unusual problems which all the theoreticians will inevitably face when trying to explain the electric and magnetic phenomena without this electrodynamics, one is instinctively hostile towards any attempt to shake its foundation... Let us assume that all the phenomena occurring in a vacuum are in perfect accordance with Maxwell's equations and have nothing to do with the constant h."

Planck's futile attempts to fit his constant somehow into the classical theory continued for a number of years and cost him a great deal of effort. In 1911, for example, he advances a new theory: emission is a discrete process while absorption is continuous. However, neither the author himself, nor the other scientists were too satisfied with this idea. Here is another quotation to illustrate the general attitude towards Planck's quantum theory, this time from Arnold Sommerfeld, the remarkable German physicist of the period: "It seems to me that the hypothesis of emission quanta, as well as the original hypothesis of energy quanta, should be considered as a manner of explanation rather than physical reality. Nothing can be more urgent for present-day physics than the elucidating the problem. Here is the key to the situation, the key not only to the theory of radiation but also to the atomic structure of matter, and today the key is yet hidden far away."

Be it as it may, Planck remained alone in his struggle with the problem. Most physicists showed no interest in his quantum hypothesis and were reluctant to recognize it. Surprisingly or not, it was fashion to blame—or so some historians of physics believe. It is a fact that some branches of science may be in and some out of fashion, and at the time the problems of the atom were definitely out.

Still the work of Planck did not remain unnoticed. It suggested that classical physics was not the final word in science. One might be unwilling to accept quanta but the importance of Planck's novel concept was obvious. Planck's constant, this "mysterious messenger from the real world", was there and no one could afford to turn blind eye on it. Its usefullness was demonstrated more than once (the reader will see it shortly) when it helped to understand phenomena unexplainable in the framework of classical physics.

EINSTEIN'S LIGHT QUANTA

Photoeffect once more. It was Einstein who first realized all the significance of Planck's results and made use of his constant. As you remember, light striking the surface of a metal knocks electrons out of it. This is the photoeffect we already discussed at some length in Fourth Story. What is the most remarkable (let me remind you), the energy of the ejected electrons does not depend on the intensity of the incident light. Not, for example, on how far apart the metallic plate and the source of light are (see back to Fig. 25).

From the wave point of view, this is sheer nonsense: surely, if a source is placed nearer to a plate, more energy will reach the plate and, accordingly, more energetic the ejected electrons should be. But this is not the case. As A. G. Stoletov has discovered, the energy of the photoelectrons is determined entirely by the frequency of the light. The explanation was proposed by Einstein in 1905. In his picture, light is the stream of particles, each having the same energy E whatever the distance from the source, namely,

$$E = h\nu,$$

where ν is the frequency of light. Note that, after Planck himself, this was the first time that his constant was used by any other physicist. But Einstein went farther than Planck. Scientists were now forced to accept that not only the emission and absorption of light occurs in tiny portions of energy, quanta, but, what is more, light is made up of such portions. Light quanta (later to be called photons) are particles that travel in a vacuum at the speed of light, i.e. about 300 000 km a second.

That was a forward step of extreme importance. If Planck found just a new way to explain emission and absorption, Einstein was much more radical: he attacked the basic principles of classical physics. Electromagnetic field is discontinuous, he argued, and is composed of individual quanta. Once produced, the light quanta live on as individual particles. In a real sense one can say: "Einstein was much more at home in Planck's theory than the author himself" (Lev Landau).

Doubts and objections. Einstein's theory was not accepted immediately and unanimously: too large a number of physical phenomena had been explained in the framework of the well-esteemed wave theory of light. As Einstein himself much later wrote, "The wave theory... has proved to be correct in representing purely optical phenomena and will probably not be replaced by any other theory. But," he went on, "one must, however, keep in mind that the optical observations are concerned with temporal mean values and not with instantaneous values, and it is possible... that ... the theory of light... may lead to contradiction with observations if we apply it to the phenomena of the generation and transformation of light."

With Einstein's photoelectric theory, the age-old argument about the nature of light was revived. On the one hand, light behaved like wave, on the other—it resembled a particle. What was light, after all? How possibly could wave and particle be integrated in one phenomenon? Partly, the question was answered in our Fourth Story. Eistein firmly believed that this duality is an inherent feature of light, that light is in a real sense endowed with both corpuscular and wave properties.

Another stumbling block was the relationship $E = h\nu$. If light is made up of particles, what on earth is the ν? What kind of oscillation is it meant to describe? Or, perhaps, frequency is no longer a characteristic of an oscillation process? How possibly can energy be associated with frequency? When stormy waves are rolling onto the beach, their energy is determined by their amplitude, not by frequency.

The theory of the photoeffect with its mysterious combination of apparently incompatible wave and corpuscular properties was not recognized for a long time. Here is a bizarre footnote to our story. In 1912 a proposal was presented by Planck and several colleagues that Einstein be admitted to membership in the Royal Prussian Academy of Science. These are the words from the document: "... that he may sometimes have missed the target in his speculations, as, for example, in his theory of light quanta, cannot really be held against him".

But, however, paradoxical, Einstein's theory was being confirmed by experiment. Direct experimental tests of Einstein's equation showed its correctness beyond any reasonable doubt. When Einstein was awarded the Nobel Prize, in 1922, it was for his work "in the field of theoretical physics, particularly his discovery of the law pertaining to the photoelectric effect." At long last the quantum ideas were admitted to the Science citizenship.

Confirmation of corpuscular properties of light. This came from numerous experiments, among them from those performed by Soviet physicists. A. F. Ioffe showed that individual ejections of electrons out of the surface of a bismuth dust particle followed one another with random intervals, in accordance with the notion that photons fell on the particle randomly. In still more convincing manner, the corpuscular nature of light manifested itself in the Ioffe-Dobronravov experiment on the photoeffect from the dust particle bombarded by X-rays and later in S. I. Vavilov's experiments on fluctuations in low-intensity light beams.

Compton's effect. In 1922 the American scientist Arthur H. Compton studied scattering of X-rays. From classical standpoint, X-rays are just electromagnetic waves and their frequency after the scattering should be therefore the same as before. It was not. Or, rather, along with this "initial" frequency, the spectrum of scattered rays included other—lower—frequencies.

As it turned out, the only way to explain the effect was to adopt the corpuscular views. Light is the stream of particles, that is, photons. In an elastic collision a photon is reflected by an electron and a part of the photon's energy is transferred to the electron. By using the laws of conservation of energy and momentum, one can easily calculate the change in the photon's energy (alias frequency) as a function of the scattering angle. We reproduce here this formula written in terms of photon's wavelength λ:

$$\Delta\lambda = \frac{2h}{m_0c}\sin^2\frac{\varphi}{2},$$

where φ is the scattering angle. This simple formula was found to be in a perfect agreement with experiment.

Before Compton's experiment it had been generally believed that the individual characteristic of a photon, its frequency, always remains the same. Now that this was disproved, the idea of the photon became more "tangible", more real.

"HIGHEST FORM OF MUSICALITY IN THE SPHERE OF THOUGHT"

The structure of atoms was another sphere of influence for Planck's constant.

What drew scientists' attention to the inner structure of the atom was the discovery of the electron (whose role in physics was already shown in Third Story; here goes another impressive example). The fact alone that an electron has a negative charge allowed some speculations on what the structure of the atom might be. In the first ever model of the atom, J. J. Thomson (the discoverer of the electron) represented it as a positively charged sphere with electrons immersed in it here and there (see Fig. 41). When unperturbed, both electrons and the positive charge were believed to be at rest, which seemed to secure the atom's stability (when in motion, the electrons should lose their energy in the form of radiation). To hold the whole structure together, some other (than electrostatic) forces were assumed to exist, of still unknown nature.

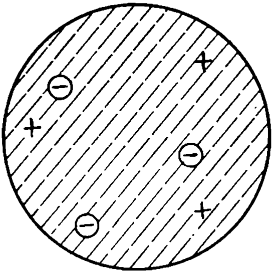

Fig. 41

Even though Thomson's model was later disproved, its significance cannot be denied: the *inner structure of the atom* became the subject of discussion. At the time, this was something bordering on blasphemy: the very meaning of the word "atom" (indivisible, in Greek) was hostile to the idea. In does not matter that the hypothesis turned out to be wrong: it stimulated investigations, the conclusions made on its basis could be tested experimentally.

Rutherford's model. The next major step was made by the remarkable English physicist Ernst Rutherford. His idea was to determine experimentally the distribution of charge in the atom. To this end, he bombarded atoms with beams of fast positively charged particles. These were alpha particles resulting from radioactive decay (see Third Story). It was known by the time that they were, in fact, doubly ionized atoms of helium, with mass about 8000 times that of an electron. The way in which the alpha particles are deflected, Rutherford argued, should allow some conclusions as to the arrangement of the atomic components. The schematic diagram of Rutherford's experiment is shown in Fig. 42. A beam of alpha particles is directed into a sheet of gold foil *M* with the thickness of as little as 400 atomic layers. Behind it, you see a screen *S*. It is made of zinc sulphide, a material that emits a tiny flash of light whenever hit by an alpha particle. Travelling at a speed of about 20 000 kilometers a second, alpha particles were scattered

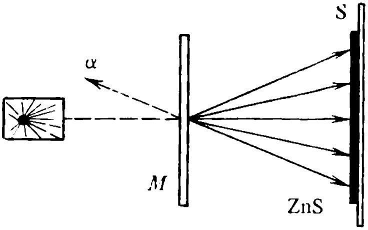

Fig. 42

in collisions with the atoms of the gold and went further to strike the screen.

But not always, as it turned out! What Rutherford quite unexpectedly observed happening was that some of the particles were scattered... backwards. This seemed incredible: the entrant particles had enormous kinetic energy. The only conclusion imaginable was that there is, inside

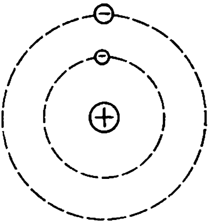

Fig. 43

the atom, "a tiny massive center carrying a positive charge". The notion of the "atomic nucleus" thus came into physics. On the basis of his experimental data Rutherford was even able to estimate the radius of the nucleus: from 10^{-12} to 10^{-13} cm. The experiments and calculations led Rutherford to his widely known model of the atom: a relatively small positive nucleus at the center and electrons well away from it.

But the question was again to be answered: what holds the nucleus and electrons together? What mechanism provides the stability of the atom? Obviously, an electron cannot remain at one place: it would be attracted by the positive nucleus. Perhaps, it rotates around the nucleus like the planets around the Sun? This was the "planetary model" of the atom.

Objections, however, came without any delay. As Maxwell had shown, any charge, when in accelerated motion, generates electromagnetic waves. But an electron moving in an orbit around the nucleus *is* being accelerated. It should therefore lose continually its energy (in the form of radiation) until it approaches the nucleus and falls onto it. All this would only take about 10^{-8} s, as estimates showed. How should this be reconciled with the remarkable stability displayed by atoms? And now—what about chemistry? We know that all the atoms of a given chemical element are identical. But how can this identity be provided here? Take, for example, hydrogen, the simplest atom of all. At any instant the single electron of each hydrogen atom will be moving around its respective nucleus in its own particular orbit, so that various atoms will not have too much in common. The Rutherford model, as we see, disagreed both with chemistry and the laws of classical physics.

But there was still another predicament. If an electron is rotating around the nucleus, it radiates light whose frequency concides with that of the rotation. When the electron falls onto the nucleus (which seems unavoidable) its radius diminishes, the light frequency continually increases and the radiation spectrum of the Rutherford atom must therefore be continuous. Experiment showed, however, that atomic spectra were in fact the sets of discrete lines, each type of atom having its own set (see Fig. 44). These sets were, indeed, the "identity cards" of atoms, widely used in chemical analysis throughout the whole of the nineteenth century.

Not only were they used, though, but many attempts were made to understand the underlying regularities. It was on this way that the mystery of the atom was ultimately unveiled. The first important step was made in 1885 by Johann Balmer. He found that for the hydrogen atom the

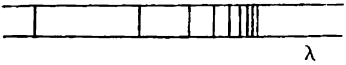

Fig. 44

wavelengths of the regular array of spectral lines are well described by a simple empirical formula

$$\lambda = \frac{\lambda_0 n^2}{n^2 - 4},$$

where λ is the wavelength, λ_0 a constant and n a whole number. Later, J. Rydberg showed that for many elements the arrangement of spectral lines may be written in the form:

$$\nu = cR_\infty \left(\frac{1}{4} - \frac{1}{n^2}\right),$$

where ν is the frequency of radiation, and

$$R_\infty = 10\ 973\ 731\ \text{m}^{-1}$$

is another important natural constant, the Rydberg constant, which is also included in our Table.

Intuitively, it was clear for many that the Rydberg formula should be somehow related to the mechanism of emission of light by atoms. But how? Nature lingered with the answer and only a few physicists were involved in the problem (which was rather out of favor, as we have seen). It was not until 1913 that the key to the understanding of the atom was at last found.

The Bohr atom. In this year a young Danish physicist Niels Bohr (1885-1962) advanced his model of the hydrogen atom, based on (and meant to explain) its atomic spectra.

Describing the situation in physics at the time, Einstein wrote years later: "That this insecure and contradictory foundation was sufficient to enable a man of Bohr's unique instinct and sensitivity to discover the principal laws of the spectral lines and of the electron shells of the atoms, together with their significance for chemistry, appeared to me as a miracle—and appears to me a miracle even today. This is the highest form of musicality in the sphere of thought." One cannot but agree with the great man.

However, the method used by Bohr in formulating his theory was much the same that Planck employed to derive his black body radiation formula. That is to say, no real justification was there behind it. As the first step, Bohr believed, it is worth-while to find an atomic model more or less consistent with observed spectral regularities. To fill the model with real physical content will be the second step. Accordingly, Bohr was not overscrupulous in dealing with physical laws. To solve his particular problem, he just chose some of them, very much arbitrarily, and added several quantum assumptions. It was miracle indeed that such home-made model was workable at all—but it was.

The cornerstone of Bohr's approach was Planck's idea that in an elementary act of emission, an atom releases a small amount E of its energy in the form of light:

$$E = h\nu$$

(ν being the frequency of the emitted light).

To provide for the stability of the atom, Bohr risked at a very artificial and utterly unfounded assumption that, of all perceivable orbits, only a few are actually available for the electron. With nothing more to lose, he assumes further that, when in one of these allowed ("permissible") orbits, the electron does not radiate. The emission only occurs when an electron goes from one of these orbits (with an energy, say, E_1) to another (E_2). The energy $h\nu$ of the light quantum (photon) produced in this transition is

$$h\nu = E_1 - E_2.$$

Needless to say, the time-honored laws of classical physics are treated here with little respect (to put it mildly). Bohr's electron is allowed to have only fixed values of energy, it does not radiate when it certainly should and the frequency of the emitted light is determined not by the motion of the electron but by changes in its motion. At the time, these proposals were considered quite naturally as nothing less than absurdity. But the facts were on Bohr's side. Experimental data were in excellent agreement with his model.

This success stimulated Bohr's further efforts. An important question to answer was, how the permissible orbits were to be found? Since, in an electron's motion in an orbit, its momentum $m_e v$ and the orbit's radius r are constant, the quantity $m_e vr$ also remains unchanged. Bohr notices that the dimension of this quantity is that of Planck's constant and formulates a rule to determine the radii of the permissible orbits:

$$2\pi\, m_e vr = nh,$$

where n is a whole number. It is wonderful that, however ill-founded, this relationship, taken together with Newton's second law, enabled Bohr to calcutate the radii of electron orbits, the energies of stationary states (nowadays called atomic energy levels) and the radiation frequencies of the hydrogen atom—all in full agreement with experiment.

Limitations of the Bohr model. Certainly, Bohr's theory had only limited success. The hydrogen atom was the only one which could be described: the model failed to predict the spectra of other atoms. The chemical properties of elements also found no satisfactory explanation. All this is hardly surprising for Bohr's basis assumptions are, after all, completely groundless. What Bohr actually performed, as Planck had done, was to "patch up" the classical laws. Nevertheless, it was obvious that the idea of quantization of the atom's energy was somehow a good one, even though Bohr did not see why. And, of course, Planck's constant was again one of the leading characters of the play.

WAVES OF MATTER

It was clear that the success of Bohr's model (however limited) could not be just a matter of casuality. It was true that the prerequisites of the theory were unfounded and it was only natural that Bohr's work appeared for many as nothing more than playing with formulas. Still the positive results could not be denied. There was a feeling that this was the right track to follow and the understanding of the atom was somewhere close at hand. All at once, Bohr's assumptions and, above all, his quantization conditions for electron orbits, became the subject of the most intense scientific interest.

The most fruitful suggestion was made by a young French physicist Louis de Broglie. Generally, and only quite naturally, all the phenomena associated with the electron had been treated from the corpuscular point of view. (How else?) De Broglie seeks for a generalizing idea, capable to combine corpuscular with wave approaches... he goes so far as to treat the electron as a wave.

That was a revolutionary breakthrough, only to be compared with Einstein's revelations. Wave-particle duality, thus far a prerogative of the photon alone, is extended by a Broglie to include —in principle—all material objects. For him, *all of them are endowed with wave properties* similar to those of light.

Derivation of Bohr's quantization conditions. De Broglie found a simple relationship between the wavelength and momentum of any particle. To get an idea of his reasoning, let us take, for example, the photon. On the one hand, its energy $E = h\nu$, on the other, it may be expressed in terms of the photon's momentum p and the speed of light: $E = pc$. We have, therefore

$$h\nu = pc.$$

Since $\nu = c/\lambda$, one finds

$$\lambda = h/p. \tag{14}$$

De Broglie applies this relationship to all microparticles and in doing so the quantization condition for Bohr's electron is obtained in one fell swoop. The derivation is as simple as this. The permissible orbits are such, de Broglie states, that their length is a multiple of an electron's wave, which is, in fact, the condition for the existence of standing waves:

$$n\lambda = 2\pi r,$$

where n is a whole number and r is the orbit's radius. Substituting into this formula the relationships $\lambda = h/p$ and $p = mv$, we obtain

$$2\pi\, mvr = nh.$$

If we associate with an electron a certain wavelength, this condition acquires a new meaning: it is no longer a (rather unusual) property of the atom, but a property of the electron itself. Once again it becomes clear that, as far as microparticles are concerned, only quantum ideas are to be used. Once again h enters physics to defend its title of a universal physical constant.

The wave properties of the electron needed experimental check. One way that this could be done was suggested by de Broglie himself: if the stream of electrons is sent through a very narrow slit, it should exhibit a diffraction pattern.

The first direct confirmation of de Broglie's ideas came, however, in somewhat different way. In 1927 the American scientists C. Davisson and L. Germer studied scattering of low-energy electrons from the surface of a metallic crystal. Very distinctive maxima were observed in the distribution of the scattered electrons (see Fig. 45). This result can only be explained if wave properties of the electron are taken into account. Each atom of the crystal may then be regarded as a source of a secondary wave. If d is the interatomic separation and the angle θ indicates the point on the screen, then we have a very simple receipt where the maxima are to be found or, in other words, where the waves are mutually amplified. This is the equality $n\lambda = d \sin \theta$, where λ is the wavelength of the electrons. Both d and θ are measurable and λ can be easily calculated. The result was within one percent of that predicted by the de Broglie theory.

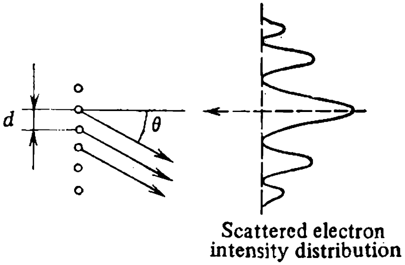

Fig. 45

In a more elaborated experiment, the Soviet scientist V. A. Fabrikant and his coworkers have shown that the wave properties are characteristic not only of a beam of electrons, but of an each individual electron. In their scheme, the scattered electrons struck the screen very rarely or, to be more precise, the time interval between two successive hits was 10 000 times larger than the time it took for an electron to go through the apparatus. The experiment showed that the diffraction pattern was independent of the electron beam intensity. It was a direct proof of the wave nature of a single electron. At present we know quite a lot about the wave properties of microparticles (more on that in Sixth Story) and *the wave nature of matter is an unquestionable fact.*

The theory of de Broglie and its experimental proof showed that when we come to discuss the behavior of microparticles, the old classical characteristics such as coordinates and velocities can no longer be used. Since microparticles are particles as well as waves, a new type of description should be found for them which would be different from that of classical physics.

Such a description has been given by *quantum mechanics* where the behavior of microparticles is represented by so-called "wave functions".

As compared with classical mechanics, this new mechanics studies by far more fundamental properties of matter.

THE MEASURE OF UNCERTAINTY

Is uncertainty so certainly bad? Why, you would answer, so it seems. No one is too happy about uncertainties. I'd like, for example, to spend my vacation on the Baltic Coast (instead of Mediterranian), but the weather is so uncertain there!... Well, it looks like uncertainty is indeed undesirable.

No wonder that this concept was received rather skeptically when it first emerged in microphysics in the form of no less than the "uncertainty principle". It took quite a time for scientists to comprehend its significance. By now, its positive and constructive role is fully recognized. For us here, this principle is another example of application of Planck's constant.

Uncertainty relations. To see, where does it come from, let us look in some detail at the electron diffraction experiment. It will be clear that it is the combination of wave and particle properties that is behind the scenes.

Figure 46 shows the schematic diagram of the experiment. The electron beam directed along the axis y passes through the diaphragm D of the width d, and gets to the screen S. The de Broglie theory predicts that the distribution

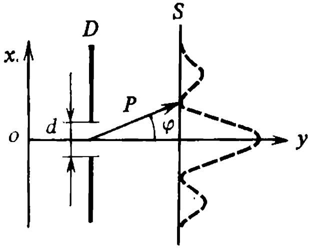

Fig. 46

of the electrons over the screen will be of the kind shown by the dashed line. This means that the maximum intensity of the diffracted electrons will be found on the axis y and the first minimum corresponds to the angle φ given by the relation $\sin\varphi = \lambda/d$. So much for the wave picture.

Now let us treat the electrons as particles. At the instant when an electron passes through the diaphragm, its x-coordinate is only known with an error equal to the width of the diaphragm:

$$\Delta x = d.$$

After the diaphragm, the electron changes the direction of its motion which means that p_x, the projection of its momentum on the axis x, will no longer be zero. If we consider only the first maximum, we have $0 \leqslant p_x \leqslant p \sin\varphi$.

But $\sin \varphi = \lambda/d$, so that

$$\Delta p_x \approx p\frac{\lambda}{d}\,.$$

Susbstituting into the equation the de Broglie wavelength $\lambda = h/p$, one obtains:

$$\Delta p_x \approx \frac{h}{d}$$

or

$$\Delta x\ \Delta p_x \approx h. \tag{15}$$

Quite similarly, we write for the other two coordinates:

$$\Delta y\ \Delta p_y \approx h;\ \Delta z\ \Delta p_z \approx h.$$

These are Heinsenberg's uncertainty relations, after the distinguished German physicist Werner Heisenberg who first derived them rigorously. Admittedly, the way in which they are obtained here is no more than an illustration of the idea.

Physical meaning of the uncertainty relation. Let us analyze equation (15). It tells us that if, in trying to describe the behavior of a microparticle, we stick to old classical notions (like coordinate and momentum), we shall not get very far. Or, more precisely, we will not be able to do this as accurately as we would like to. The more accurately we determine the coordinate of a particle, the less accurately we know its momentum (or velocity):

$$\Delta v_x \approx \frac{h}{m\Delta x}\,.$$

Isn't it a little bit disheartening? Does not it mean that Nature puts some restrictions on our knowledge of microworld? The right answer is: "No". The real meaning of equation (15) is that we are dealing here with the objective properties of micro-objects, that this is just the way things are. Micro-objects are neither particles nor waves and it is impossible to describe them in terms of "commonsense" classical notions. The wave-particle duality of micro-objects should be interpreted as their potential ability to behave differently in different conditions. Let us look back at the electron diffraction experiment, Fig. 46. We saw that, in its interaction with the diaphragm, an electron manifests itself as a wave—but it strikes the screen as a hundred-percent particle. Electrons and other microparticles are very special and specific natural objects, not to be described in the framework of our usual concepts. We cannot in principle visualize them.

But, to leave these deep waters, let us now look at the uncertainty principle at work. For we have already mentioned—and so it is—that, in the hands of physicists, this principle is quite a good tool to obtain, very simply and vividly, most important information about micro-objects.

Why does not the atom collapse? As you may remember, a very important question remained unanswered in the Bohr model, namely, why an electron, when rotating about the nucleus, does not radiate energy (which would lead to its fall onto the nucleus)? Bohr has nothing to say on this: he simply and honestly postulated it. But let us try to use the uncertainty principle. If an electron is moving in an orbit, we may argue that it is localized in a region of about 10^{-8} cm in size (such are the dimensions of atoms). If it falls onto the nucleus, it will be localized in a much smaller region, of about 10^{-12}-10^{-13} cm in size (typical dimensions of nuclei). But then, as equation (15) shows, its velocity increases by a factor of about 100 000. The electrostatic attractive forces would not be able to hold such an electron within the nucleus: it would leave it and go free. The uncertainty principle thus shows us very clearly that the electron simply *cannot* fall.

Do electron orbits exist? From classical physics, an electron in an atom has a speed of the order of 10^8 cm/s. Since the dimensions of the atom are something like 10^{-8} cm, we obtain from equation (15) the uncertainty in the electron's velocity:

$$\Delta v_x \approx \frac{h}{m\Delta x} \simeq \frac{6.6 \times 10^{-27}}{9 \times 10^{28} \times 10^{-8}} \simeq 7.0 \times 10^8 \text{ cm/s},$$

that is to say, the error in determining the velocity is comparable with the velocity itself. This is, in fact, the answer to our question. The notion of electron orbits turns out to be invalid. We see once again that, to describe micro-objects, new concepts should be introduced. Of these, the concept of probability is, perhaps, the most important in quantum mechanics. We may not speak of orbits, it is only meaningful to speak of the *probability* to find the electron at a given distance from the nucleus.

Necessity and chance. We saw in our Second Story what difficulties had to be overcome on the way to the proper understanding of gases. The systems containing large number of particles required for their description an entirely new approach, that of statistical physics. It is worthwhile here to raise this question once again, when the description of motion in micro-objects is being discussed.

In classical physics one solves Newton's equations and, provided the initial conditions are specified, the future motion of a particle is fully determined. The laws of classical physics are therefore dynamical ones. Elements of randomness (statistical description) are only relevant when we study systems of large number of particles, for example, gases.

In quantum mechanics designed to describe the properties of microparticles, the situation is totally different. Statistical, or probabilistic, approach is applied to the motion of one single particle. Whether or not we shall find the electron at a given point near the nucleus—this is a matter of chance. It is the distribution of these chances—or probabilities—which is certain. Quantum mechanics is an *inherently statistical theory*.

Correspondence principle once again. There is another interesting consequence of the uncertainty principle. Let us consider a particle whose mass is, say, 10^{-12} g. Small particle, no doubt, but, as compared with an electron, it is a huge "macroparticle". If its position is determined to within 10^{-6} cm, equation (15) tells us that the error in the velocity measurement is about 10^{-8} cm/s. That is to say, for all practical purposes its velocity can be measured with arbitrarily high accuracy. The correspondence principle is on duty! When dealing with heavy (macro) particles, their wave properties can be ignored: classical methods are quite sufficient here.

ELECTRON SPIN

The structure of spectral lines. Planck's constant is a measure unit for one of the most important characteristics of elementary particles, their *spin*.

As we know from this Story, it was through the study of atomic spectra that Niels Bohr came to his model, outstandingly successful in many respects. As time went on, however, new problems emerged. The first one was the so-called fine structure of the hydrogen spectrum. This phenomenon revealed itself to spectroscopists as the "state of the art" had advanced and higher resolution of the hydrogen spectra had become possible. Certain spectral lines that had formerly been observed as isolated single lines were now seen to be closely spaced double or triple lines. Another problem was the Zeeman effect—the splitting of spectral lines in a magnetic field.

Quantization of magnetic moment. To illustrate how all this was explained—here is a simple and elegant analysis given by Einstein. If we imagine an electron as a little ball of mass m_e, moving in an orbit of radius r at a speed v, its angular momentum is

$$L = m_e vr.$$

But a rotating electron is an electric current, isn't it, and as such it must form a magnetic moment. This orbital magnetic moment of the electron is

$$P_m = \frac{IS}{c} = \frac{evS}{2\pi rc} = \frac{ev\pi r^2}{2\pi rc} = \frac{evr}{2c}.$$

The ratio P_m/L turns out to be constant:

$$\frac{P_m}{L} = \frac{e}{2m_e c} = \gamma.$$

Since, in Bohr's theory,

$$L = n\frac{h}{2\pi},$$

we see that the orbital magnetic moment of the electron is also quantized:

$$P_m = \gamma L = \gamma n \frac{h}{2\pi} = n \frac{eh}{4\pi m_e c} = n\mu_B.$$

The constant μ_B has come to be known as Bohr's magneton and its value is

$$\mu_B = 9.2741 \text{ Joules/tesla}.$$

The discreteness of the orbital magnetic moment was confirmed in direct experiments. What was disturbing, however, the experimental value of the coefficient γ turned out to be twice the theoretical one. The immediate suspicion was that there might exist some angular momenta (and, accordingly, magnetic moments) other than orbital.

Every one knows, for example, that the Earth, apart from its orbital motion (and orbital momentum) is also involved in rotation about its axis (and has therefore an angular momentum of its own). It was, perhaps, this simple analogy that suggested to the Dutch physicists G. Uhlenbeck and S. Goudsmit the idea to ascribe to the electron an intrinsic angular momentum $(1/2) \times (h/2\pi)$, and an intrinsic magnetic moment equal to Bohr's magneton. The hypothesis explained perfectly well the disagreement between the experimental and theoretical values of γ.

For quite obvious reason, this new angular momentum of electron was given a name "spin". It became later clear that this is one of the most fundamental characteristics of elementary particles. For example, it is spin that determines the behavior of individual particles in large ensembles. Spin, as we shall see later, forms the basis of the elementary particle classification.

This brings us to the end of the Story. We have told you the story of Planck's constant and have shown its dramatic way in physics, until recognition. "The constant h", Planck wrote, "is a mysterious messenger from the real world, which appeared on the scene again and again in various measurements; which, in doing so, more and more urgently demanded its own place in the physical picture of the world but was at the same time so inconsistent with this picture that, in the end, it broke the frame of this picture, too narrow for it." Planck's constant is associated with most fundamental properties of the microworld, it gives us a much deeper insight into natural phenomena.

SIXTH STORY

Jig-saw in Earnest or the Tale of the Masses of the Proton, Neutron and Other Elementary Particles

HOW TO DISASSEMBLE AN ATOMIC NUCLEUS?

Thus far, only two universal physical constants in our Table remain undiscussed. These are the rest mass of a proton, m_p, and the rest mass of a neutron, m_n. Let us see, first of all, how did these two particles come into physics.

The reader is not unaware, of course, that the proton and neutron are elementary particles. Today, this elementary fact is even taught at school, but in the early 20th century it was at the center of most intensive research work. One of the intriguing physical problems of the time was the structure of the atomic nucleus. It was in solving this problem that the two particles were discovered. What is more, this problem gave birth to an utterly new branch of science, elementary particle physics, that led to the discovery of a great number of new elementary particles: we know now well over two hundred of them. We have learnt a lot about their properties: let us mention, for example, that elementary particles can change one into another. And, of course, a great deal of new problems have emerged, which fact, we hope, will not cool off our reader. Elementary particle physics is the front-line of science and if there are some uncertain questions—well, it may be you who will solve them.

For the moment, however, let us look back at Rutherford's experiments that resulted in his planetary model. Studying the alpha-particle scattering from a gold foil, Rutherford observed that some of the particles were scattered backwards. Since both the mass and speed of alpha-particles were quite large, the only reasonable suggestion was that, to throw an on-flying particle back, some enormous force must operate within an atom. The further natural assumption was that there was a small region within the atom where all its positive charge was concentrated (see Fig. 43). The region was given the name *nucleus* and its size was estimated to be 10^{-12}-10^{-13} cm. The question now presented itself: what is the structure of the nucleus?

It was much easier to ask than to answer. To begin with, the object itself was too small for even most lively imagination. The "number of experiments" was very limited: physicists knew just a little bit about radioactive decay and the alpha-particle scattering. And all that, one should remember, when the very existence of the atom had not still been confirmed directly.

In this situation, it was difficult to say anything definite about the nucleus. And yet, some hypotheses were being proposed and, if possible, tested experimentally. Rutherford, when advancing his atomic model, succumbed to natural temptation to compose the nucleus of alpha-particles, on the grounds that "it is alpha-particles that are emitted by radioactive substances". Since, on the other hand, beta-particles were another decay product, logic demanded that electrons also be included into the structure of the nucleus. All the more so because alpha-particles are doubly (positively) charged and, therefore, might only form even charge nuclei, which is somewhat disheartening. The inclusion of electrons seemed to save the situation in that all the spectrum of nuclear charges became available: $+e$, $+2e$, $+3e$ and so on.

These ideas seemed to be supported by a discovery made by the English chemist F. Soddy at the beginning of the twentieth century. He found that the products of radioactive decay, while showing identical chemical properties, differed sometimes in their atomic masses. Such products were given the name "*isotopes*" and their existence sharply disagreed with the notion that nuclei are made of alpha-particles only. Soddy assumed, therefore, that masses of alpha-particles add up to give the mass of a nucleus, whereas its charge is given by the difference between the total charges of the alpha-particles and electrons. About the same time, van der Bruk of Holland put forward a hypothesis that the charge of a nucleus is equal to the number the element has in Mendeleev's periodic table. This hypothesis was soon afterwards confirmed—another indirect evidence of the deep insight of the great Russian chemist. Thus the first ideas were formed on the structure of the nucleus. It should contain alpha-particles in a number needed to provide a given atomic mass; and electrons in a number needed to place the nucleus in a required square of the periodic table.

This model proved to be wrong, though. And you know why, of course: it is because of the uncertainty principle. It was pointed out in Fifth Story that the localization of an electron within a nucleus leads to a large uncertainty in its speed—too large, indeed, for the electron to stay there. Very simple, isn't it? The fact is, however, that at the time we are talking about, the uncertainty principle was still unknown and there was nothing criminal about this model.

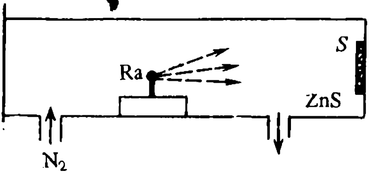

Fig. 47

The discovery of the proton. In the year 1919 an important event took place in the then young nuclear physics: Rutherford discovered, when bombarding nitrogen atoms by alpla-particles, that some new particles went out of the atoms. The schematic diagram of his experiment is shown in Fig. 47. The distance between the radioactive source and the screen *S* (covered with ZnS already familiar to you) was too large for the particles to overcome: all of them were absorbed by nitrogen. And yet, quite distinctive flashes were observed on the screen, no doubt of some other origin. The flashes disappeared if nitrogen was replaced by oxygen, thus suggesting that this new kind of emission had something to do with transformations of nitrogen struck by alpha-particles. The reader remembers, of course, the method used by J. J. Thomson to determine the mass and charge of the electron. Rutherford reproduced the same experiment to identify the unknown particles. They turned out to be the nuclei of hydrogen, H^+, and the process that produced them could be written as

$$^{14}_{7}N + {}^{4}_{2}He \rightarrow {}^{17}_{8}O + {}^{1}_{1}H.$$

(In this "nuclear reaction" we use the modern notation according to which a superscript shows the atomic mass and a subscript—the nuclear charge of the element.)

These new particles Rutherford called *protons* (meaning "simplest" in Greek), and that was before long that a direct evidence for their existence was obtained. This was done by observation of protons' tracks in *Wilson's chamber*, a unique physical instrument, certainly worthy of describing by itself. It is, in essence, a vapor-filled vessel, of which one wall is made of glass and another is connected with a piston. When the latter is abruptly pulled out, the vapor gets supersaturated and, if some condensation centers are present (say, dust particles or ions), fogging takes place. The result is that the path of an ionized particle becomes visible and may be photographed (this is shown schematically in Fig. 48). The length of the track and the density of the droplets characterize the energy of the particle. As to its charge and momentum, they may be determined by placing the chamber into a magnetic field and measuring the track's curvature.

With the use of Wilson's chamber, the mass of the proton was measured to be

$$m_p = 1.6726 \times 10^{-24}\ \text{g}.$$

The discovery of the proton was certainly a breakthrough in nuclear physics. Together with electrons and alpha-particles it provided another possible building block for the structure of nucleus.

The hypothesis of the neutron. It was very tempting to think of the nucleus as just made up of protons. But, of course, the inclusion of electrons became again inevitable. Take helium, for example. Its atomic mass is 4, so that its nucleus must contain 4 protons. But the charge of the helium is 2 which means that electrons (two of them) have to be added. And still another "but"—we know this is impossible because of the uncertainty principle. Experimental data available were thus insufficient to produce a good theory of the nucleus.

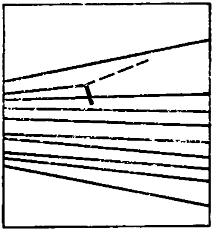

Fig. 48

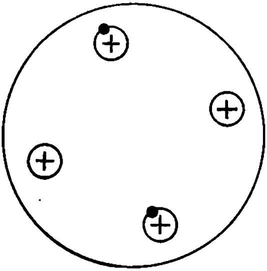

Fig. 49

The next important step is again associated with the name of Rutherford. He proposed in 1920 that still another elementary particle should exist, having no charge and a weight equal to that of a proton. Rutherford called his hypothetical particle the *neutron* and speculated that it might consist of a proton and an electron very tightly bound together. With this idea accepted, look, for example, what the structure of a helium nucleus should be (Fig. 49). At the time, nobody thought that such a "doublet" would be very soon discovered.

But so it happened. Intensive search for the neutron began, and once again the alpha-bombardment particles turned out to be very helpful. In 1930, the German physicists Bothe and Becker observed an unusual radiation when alpha-bombarding berillium. It left no tracks in the Wilson chamber and was capable of getting through thick lead walls. This radiation was generally assumed to be gamma-rays, the electromagnetic radiation with high-energy quanta. In 1932 Irene and Frederic Joliot-Curie, the well-known French physicists, made this "berillium radiation" to bombard a paraffin target. They found that a great number of fast protons were knocked out of the target in the direction of the radiation. By measuring the energy of the protons, it was possible to estimate the energy of the supposed gamma-quanta. It was found to be quite high, of the order of 5×10^7 eV (1 eV being the energy acquired by an electron that has fallen through a voltage difference of 1 V).

The discovery of the neutron. In Rutherford's laboratory his disciple J. Chadwick exposed a variety of materials to the mysterious new radiation. He found that, hitting various targets, it produced not only protons, but other recoil nuclei as well, such as the nuclei of nitrogen, argon and so forth. Chadwick measured the energy of the recoil nuclei and recalculated from this the energy of the alleged quanta. The results for various targets dissapointingly disagreed. The calculations from nitrogen nuclei gave for each quantum 9×10^7 eV, while from argon nuclei 1.5×10^8 eV. One had definitely to abandon the idea that the radiation was electromagnetic. Besides, another question was hard to answer: if gamma-quanta had no rest mass (which is a fact), how possibly could they set into motion the massive nuclei of nitrogen and argon?

The high penetrating power of the new radiation suggested that it might be composed of neutral particles. The assumption that the supposed particles were of approximately the same mass that protons, enabled Chadwick to obtain excellent agreement with his experimental results. Further measurements showed that the mass of this new particle was

$$m_{\mathrm{n}} = 1.67495 \times 10^{-24}\ \mathrm{g}.$$

A new particle quite naturally named neutron came into physics.

The modern model of the nucleus. A new model of the nucleus, the *proton-neutron model*, was immediately proposed by the Soviet physicist D. D. Ivanenko and the German physicist Werner Heisenberg. According to the model (see Fig. 50), a nucleus is composed of both protons and neutrons. The number of protons is equal to the number of electrons in the atom; the number of neutrons is the difference between the atomic mass of the element and the net mass of the protons. Soddy's isotopes, in this scheme, differ in a number of constituent neutrons, so that their chemical properties, being determined by electron structure, are identical. The model has been thoroughly tested and is now widely accepted.

Which, unfortunately or not, does not mean at all that the problem of the nucleus is solved. Quite to the contrary, a number of new questions have arisen. We know, for example, that a strong electrostatic repulsion should exist within a nucleus between the constituent protons. If so, what holds them together? If, further, there are no electrons in the nucleus, how does it happen that they emerge in the process of radioactive decay (as beta-particles)? We shall try to answer these questions in the next sections. In doing so, we shall say more on the physical significance of the new constants and their role in the modern physics will be made clearer.

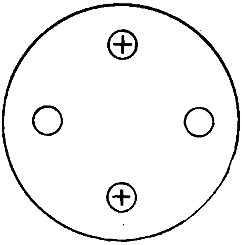

Fig. 50

"WEIGHING" ENERGY

Were the rest masses only weight characteristics of the proton and neutron, even then they would be of major importance in physics. But there is much more to it than that. Mass, as we know, is energy. These two masses are also associated with energy—produced, for example, by the Sun for so many billions of years.

Einstein's formula can be checked. In our Fourth Story we learned famous Einstein's relationship between mass and energy:

$$E = M_0c^2.$$

What this means is that the energy of one gram of any substance is 9×10^{13} J. Were we able to liberate this energy and put it to use, we wouldn't care a bit about the world's energy resources, oil and coal in the first place. Industry and agriculture would thrive and some of the world problems would not exist at all. Thus far in the book, we are ignorant on how this fundamental relationship has been tested (if at all). It was just the discovery of protons and neutrons that gave physicists such a possibility.

Mass defect. Having established that nuclei are composed of protons and neutrons, physicists soon discovered that the rest mass of any nucleus is always less than the net rest mass of the constituent particles. The deficiency ΔM was christened as the "mass defect". Deuterium, for example, ($^2_1$H, a heavy isotope of hydrogen, with one proton and one neutron in the nucleus) has the mass defect of 3.96×10^{-27} g. This is a very small figure, you might say, but the corresponding energy is quite substantial:

$$E = \Delta Mc^2 = 3.96 \times 10^{-27}\text{ g} \times 9.0 \times 10^{20}\text{ cm}^2/\text{s}^2 = 2.25 \times 10^6\text{ eV}.$$

Binding energy. The mass defect being always positive, an immediate conclusion is that when a number of individual particles come together to form a nucleus, a considerable amount of energy is released. By the law of conservation of energy, it is obvious that if one is going to split the nucleus into its constituent particles, the same amount of energy must be applied. When a nucleus is formed from protons and neutrons or (which is also possible) from other lighter particles, its binding energy is released in the form of electromagnetic radiation, that is, as high energy gamma-quanta. It is to this mechanism that we obliged for the enormous energy which is being generated in the depths of the Sun and then generously sent to us here on the Earth.

The hypothesis of the nuclear origin of solar energy was first put forward by Atkinson and Houthermans in 1929. Ten years later H. Bethe suggested a chain of reactions in which four protons, coming together, form one alpha-particle (the nucleus of helium). The excess of positive charge is carried away by two particles having the mass of an electron but charged positively. These particles were later given the name *positrons*. The mass (and, correspondingly, energy) balance of Bethe's processes is as follows:

the mass of a proton (^1_1H) is 1.6726×10^{-24} g,
the mass of an alpha-particle (^4_2He) is 6.6439×10^{-24} g,
the mass of a positron 0.0009×10^{-24} g.

The mass defect of the reaction is 0.0489×10^{-24} g which is equivalent to the energy release of about 2.5×10^7 eV.

It was very tempting, of course, to realize the nuclear synthesis reaction in terrestrial conditions. These efforts, however, run into serious difficulties. The point is that, to fuse a pair of protons, they should be made to approach one another as close as the distance of the order of the nuclear radius, that is, about 10^{-12}-10^{-13} cm. Clearly, the electrostatic repulsive forces will be very powerful at this distance and the energy to overcome them should, correspondingly, be very high. So much so that, as calculations show, the nuclear substance must be heated up to temperatures of hundreds of millions of degrees. (Which means, by the way, that all the atoms will lose their electrons and what we shall have is *plasma*, the mixture of positively charged nuclei and negatively charged electrons.) Inside the Sun, such temperatures are sustained in quite a natural way, due to thermonuclear processes. In terrestrial laboratories, however, these temperatures are very hard to achieve. (What comes first to mind is that, without some precautions to ensure thermoisolation, the walls of any plasma container will evaporate at even much lower temperatures.) Today, worldwide research work is being done to find the ways to produce and confine the plasma in closed volumes (by using a magnetic field, as a rule). To harness thermonuclear energy is the top and foremost problem of the present-day world energetics.

Nuclear fission energy. In the meantime, another source of atomic energy has been mastered and used by mankind. This is the energy released in the breakdown (or splitting, or "fission") of uranium nuclei bombarded by neutrons. This effect was discovered in 1938 by Otto Hahn and Fran Strassmann in Germany:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}n \rightarrow {}^{139}_{51}\mathrm{Xe} + {}^{95}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}n.$$

One single act of such fission gives away a huge amount of energy, about 2×10^{8} eV. Since, in the process of fission reaction, the number of neutrons is increasing, the reaction becomes self-sustained ("chain reaction"). In all, the fission of 1 g of uranium produces about 2.3×10^4 kWh of energy, the equivalent of three tons of coal burnt. The first ever nuclear power plant was put into action in the USSR, in 1954. Since then, a large number of powerful nuclear plants have been built up.

Sadly enough, the remarkable achievements of physicists were used by imperialistic states for producing a barbaric weapon, atomic and neutron bombs. In 1945, in the bombardment of the Japanese cities of Hiroshima and Nagasaki tens of thousands of innocent people were killed. Today, nuclear arms race is a horrifying threat for all of mankind. But let us try to hope—and struggle—for the best.

THREE DIFFERENT SIMILAR DISCOVERIES

What we are going to tell you about in this section, are the discoveries of three more elementary particles. All the three discoveries are similar in that a new particle had been first predicted theoretically and it was only after a long period of experimental research that its existence was reliably confirmed. As Boltzmann once said, "There is nothing more helpful for practice than a good theory".

DISCOVERY I. PREDICTION OF ANTI-WORLD

In 1928, the eminent British theoretical physicist Paul Dirac predicted that an elementary particle should exist whose properties repeat those of the electron with one exception: its charge is positive. By the time, the wave properties of the electron had been well enough established and the newly developed "non-relativistic" quantum theory described its behavior quite adequately. But—at speeds much lower than that of light. Dirac extended this theory to include relativistic speeds, so that in his approach quantum mechanics and the relativity theory were put together. Dirac's equations literally forced him into the idea that the electron's twin should exist, but positively charged. For the first time, the notion of antiparticle came into physics.

This mathematical result (for such it was) was very hard for physicists to interpret. Dirac himself thought the new particle might be the proton. Strange, isn't, the proton being by far much heavier than the electron. Note, however, that apart from the proton, physicists of the time had at their disposal no other particle with a unit positive charge. As to the difference in mass, Dirac hoped it could be accounted for by the strong electromagnetic interaction between these two particles. The idea, however, was refuted by theoretical calculations of the American physicist P. Oppenheimer. The nature of the predicted particle and its very existence remained open to question.

The discovery of the positron. But experiment showed decisively that the particle really existed. In 1932 the American physicist Anderson observed in Wilson's chamber a track of some unusual particle (see Fig. 51). It turned out that this particle had the mass of an electron, but in a magnetic field was deflected in the opposite direction. This implied, of course, that it was charged positively and was therefore nothing else than the electron's antiparticle predicted by Dirac (not unreasonably called *positron*).

It was not, however, the only antiparticle predicted. In fact, Dirac's theory implied that every single elementary particle had its antiparticle. This prediction was afterwards confirmed beyond any possible doubt. In 1955 the antiproton was discovered, a particle with the same properties as the proton but again with an opposite charge. As time went on, a vast number of antiparticles has been found. Today the existence of anti-world is a fact.

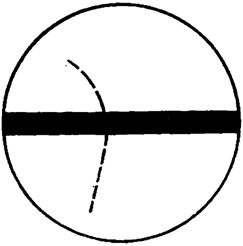

Fig. 51

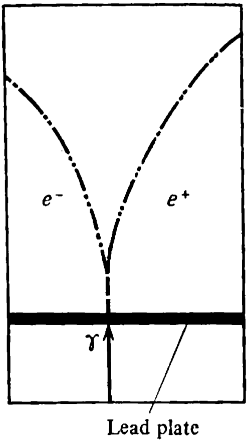

Fig. 52

Annihilation. Now there was another extremely important implication of Dirac's theory. He predicted, namely, that if a particle happens to meet its antiparticle, both of them disappear ("annihilate") and their energy is released in the form of electromagnetic radiation:

$$e + e^{+} \rightarrow \gamma + \gamma.$$

A reverse process is also possible, when an electron and a positron are produced:

$$\gamma \rightarrow e + e^{+}.$$

These predictions of Dirac's theory were also confirmed by experiment. In Fig. 52 you can see the process of production of an electron-positron pair. In going through the lead plate, the high energy gamma-quantum disappears but produces an electron and a positron forming a typical forked track in Wilson's chamber.

The phenomenon of annihilation came as another illustration to Einstein's fundamental formula $E = M_0c^2$. Indeed, the mutual transformations of "material" elementary particles into "immaterial" quanta of electromagnetic field is a further evidence for the unity of mass and energy, the unity of Nature as a whole.

DISCOVERY II. NEUTRINO

Throughout the book, it has been mentioned a number of times that the electron cannot serve as a component of atomic nuclei. No less frequently, however, it was said that, in the radioactive decay the emission of electrons may be observed (beta-rays). The first fact considered, how the second could be possible? It is only now that we can answer this question.

The story of the problem is very much like a good thriller. Indeed, if an electron leaves a nucleus, the mass of the latter remains practically the same, since the electron mass is very small. What changes, however, is the charge of the nucleus: it becomes by one unit more positive. Now, the only positive particle within the nucleus is the proton. It seems reasonable to assume, therefore, that in the beta-decay process the number of the constituent neutrons should decrease by one, that is, one neutron should disappear giving way to an electron and proton. The mass defect would then be about 9×10^5 eV. It was found, however, that the kinetic energies of the emitted electrons spanned a continuous spectrum from zero to 9×10^5 eV. The whole affair took rather a nasty turn. On the one hand, the beta-decay was a well established fact, on the other, the law of energy conservation was in danger. But this is a fundamental, not to say sacred, law of physics. Should we put up with the idea that it does not work in decay processes? Or are there some other options?

Wolfgang Pauli (1900-1978), the eminent Swiss theoretical physicist, believed they were—one, at least. He assumed that, in the beta-decay, some other particle is also emitted, which carries away the energy excess and is not detected in experiments for the simple reason that it has no charge on it and no rest mass. The idea was a risky one, of which fact Pauli was quite conscious. "Today, I've done an awful thing", he wrote, "a theoretical physicist ought never to do that. I assumed something that can never be tested in experiment." It was a courageous step, of course, but Pauli's belief in the energy conservation law was adamant.

Soon afterwards, the new particle was named the "neutrino", an Italian word proposed by the famous Italian physicist Enrico Fermi. For a long time, however, it remained nothing more than a figment of a theoretician's imagination. And yet, Pauli was wrong declaring the neutrino undetectable, even though it took another 26 years to disprove him. It was only in 1956 that the elusive particle was found by the American physicists Cowan and Reines whose exciting experiment certainly is worth of discussion in some detail.

We have already mentioned that if the nuclear decay of uranium is caused by neutrons, the number of the latter is being increased in the process. This is what actually happens in nuclear reactors and they became therefore very helpful in the study of neutrons. It was established very soon that free neutrons must decay according to the scheme:

$$n \rightarrow p + e + \tilde{\nu}_e.$$

where p is the proton, e the electron and $\tilde{\nu}_e$ the electron antineutrino. The average lifetime of free neutrons is, by the latest estimates, about 16 min. An atomic reactor, apart from neutrons, should thus produce a powerful stream of antineutrino—so powerful, indeed, that in spite of their enormous penetrating ability, there exists a finite probability to detect them. As to the specific way in which to do that, let us follow the reasoning of the experiments. As theoreticians had predicted, the following reaction should occur (however infrequently):

$$\tilde{\nu}_e + p \rightarrow n + e^+.$$

The resulting e^+ immediately annihilates with an electron

$$e^+ + e \rightarrow \gamma + \gamma.$$

The two flying apart photons may be detected by flashes they produce in an appropriately chosen material of the so-called "scintillator" (see Fig. 54 where the schematic diagram of the apparatus is shown). The second participant of the reaction, the neutron, may as well be detected. To this end, the neutron is made to wander in water for some time, until most of its energy is lost. Thus weakened, the vagabond neutron is readily absorbed by the atoms of cadmium added to the

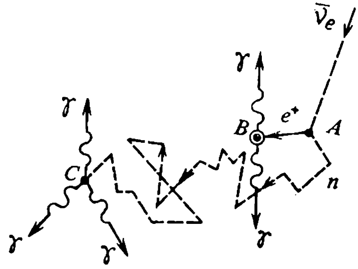

Fig. 53

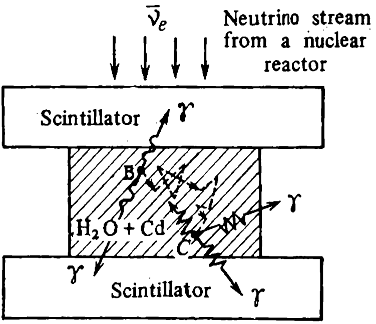

Fig. 54

water just for the purpose. In the process, a cadmium atom also emits photons, equally well registered. So, if the (anti)neutrino really exists and all goes well, we must first observe the flashes signalling the neutrino-proton interaction and some time afterwards another two flashes must be seen, caused by the capture of a neutron by cadmium (the time interval mentioned is the neutron "slowing-down" time, something like 10^{-6} s). This was just the sequence of events very distinctly observed by Cowan and Reines (at the rate of three times an hour which may be considered rather frequently). The existence of neutrino was thus definitely proved. In the family of elementary particles one more particle appeared. The predictions of theory came true again.

DISCOVERY III. THE JUKAWA MESON

The structure of the nucleus having been established, the next concern for physicists was: what holds its constituent particles together? Don't all of us know that "like charges repel"? But then the protons should repel each other within the nucleus—the more so since the distance between them is so small. None the less, nuclei are stable, at least most of them are. It is necessary to assume, therefore, that some attractive forces should act between the protons, much more powerful than the electrostatic ones. But what the nature of these *nuclear forces* could be? To find this out, some new ideas were to be developed as to the possible mechanisms of interaction between elementary particles.

A helpful idea of this kind had already been proposed by Fermi, of great significance for elementary particle and nuclear physics. He assumed that a neutron and a proton may interact with one another by emitting and absorbing an electron-neutrino pair. According to this notion, he developed a beta-decay theory from which it follows that such interaction was much weaker than electromagnetic one (by a factor of about 10^{11}). It came to be known in physics as the *weak interaction.*

Starting from this idea I. E. Tamm, of the USSR, proposed in 1934 a theory of nuclear exchange forces. His basic assumption was that *nucleons* (which is a common name for the protons and neutrons comprising the nucleus) interact by exchanging electrons with each other. This idea turned out to be wrong though: the exchange forces in question were not strong enough to provide the stability of the nucleus.

Meson. The Japanese physicist Hideki Yukawa, in 1935, advanced a hypothesis that, for a nucleus to be stable, the exchange particles might be considerably more massive than the electron. These particles were later called *mesons.*

Let us use the uncertainty principle to estimate the mass of the meson. As already mentioned, the nuclear forces should be stronger than the electrostatic repulsive forces. But the radius of their action, on the other hand, should be very small, about 10^{-12}-10^{-13} cm, which is a typical nucleus radius. In a meson-exchange process a system composed of two nucleons and a meson cannot have a definite energy. The energy uncertainty is just the energy of the exchange meson (see Fig. 55). The energy of the meson, in its turn, is the rest energy of the particle (the rest energy of a particle is the energy of the particle when at rest) plus its kinetic energy. Its minimum value is $E = m_\mu c^2$, m_μ being the mass of the meson. The lifetime $\Delta\tau$ of such temporary or,

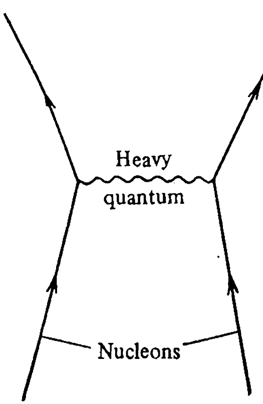

Fig. 55

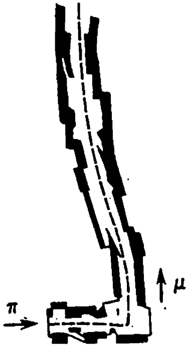

Fig. 56

to use the special term, virtual state of the system may be estimated from the uncertainty relation

$$\Delta E \Delta\tau \approx h.$$

(We have not met it yet, but it had been also obtained by Heisenberg.) Clearly,

$$\Delta\tau \approx \frac{h}{\Delta E}.$$

Assuming that the meson travels at the speed of light, the distance it will pass during this time is

$$R \approx c\Delta\tau = c\,\frac{h}{\Delta E} = \frac{h}{m_\mu c}.$$

Evidently, this is just the typical radius of action for the exchange force. But this is approximately

10^{-12} cm, so that, for the mass of the meson, we obtain

$$m_\mu \approx \frac{h}{Rc} \approx 250\ m_e.$$

All this was fine, and yet it was difficult to imagine a particle whose mass was intermediate between those of the nucleon and the electron.

Where should one look for the meson? Still, Jukawa was looking for a way to check his theory. Let us look into his reasoning. Energetic estimates will again be very helpful. Since the energy related to the meson rest mass is about 125 MeV (125×10^6 eV), it follows that this is just the amount of energy that should be imparted to the nucleon-nucleon system for a heavy quantum (meson) to be knocked out of it. But then the radioactive decay processes, with energy variation being on a much smaller scale, are of no use in the search for the meson.

It was about that time that cosmic rays were discovered, the ceaseless streams of highly energetic particles which arrive at the Earth from space. The study of cosmic rays presented an experimental evidence for the existence of mesons.

Figure 56 shows meson tracks observed in nuclear photoemulsions. As is characteristic of charged particles (which mesons certainly are), they blacken silver on their way through the emulsion. The intensity of the blackening varies along the track, which enables physicists to determine the mass and energy of the moving particles. For example, the particle we see entering the left corner at the bottom of the figure has a mass of 273 electron masses. It is slowed down, stops at the right lower corner and decays into another charged particle whose track is seen to go upwards. The mass of this "daughter" particle was found to be 207 electron masses. These two particles were later labelled as *pi-mesons* and *mu-mesons* respectively (or, for short, pions and muons). It was the former that turned out to be the meson of Yukawa. This experimental proof of his idea came as late as 11 years after the prediction had been made.

AT THE FRONTIER OF KNOWLEDGE

It is the inexorable logic of scientific progress that every discovery necessarily poses further problems. In this Story we witnessed the discovery of the proton and neutron; we then unveiled the mystery of beta-decay; we learned something about the nature of nuclear forces. And we have come gradually to a vast new area of modern physics: the elementary particles. Thus far in the book, we have met only a few of them. But with advances in experimental techniques, their list was being very rapidly enlarged. One urgently needed a clear-cut definition for the notion of "elementary particles", to say nothing of the laws that govern their mutual transformations. All this being all the more interesting that these particles are the building-blocks of the Universe, the "jig-saw" pieces to form the whole of matter. And, of course, the first priority was the systematics of elementary particles.

Systematics of elementary particles. It was a difficult task, to bring law and order into the world of elementary particles. To solve it, scientists were forced to introduce a number of new conservation laws and new particle parameters, some of them peculiar enough.

The basic idea for systematizing elementary particles seems to be very straightforward: the particles with more or less equal masses are combined to form a group (multiplet). For example, the proton and neutron are thought of as two-charge states of one particle, nucleon, or, to put it another way, they form an "isotope doublet". Isotopic triplets are formed by pi-mesons or pions (positive pion π^+, neutral one π^0 and antipion π^-) and sigma hyperons (positive sigma hyperon Σ^+, neutral Σ^0 and negative Σ^- one). Isotopic singlets (of one particle) are formed by lambda hyperon Λ^0, omega hyperon Ω^- and eta η^0 meson. Each isotopic multiplet is described as *isotopic spin* (isospin) I defined as

$$I = n' - \frac{1}{2},$$

where n' is the number of charge states in the multiplet. According to this relationship, the isotopic spin of the nucleon doublet is $I = 1/2$, and its projections I_ξ on a certain "direction" in the imaginary isospin space are $+1/2$ for the proton and $-1/2$ for the neutron. The projections of the isospin for a particle and its antiparticle are opposite in sign.

An analysis of elementary particle transformations showed that, surprisingly, K-mesons ("kaons") and hyperons always appeared and disappeared only by pairs. The examples are:

$$\pi^- + p \to K^0 + \Lambda^0,$$
$$\pi^- + p \to K^+ + \Sigma^-,$$
$$\pi^+ + p \to K^+ + \Sigma^+.$$

To explain this fact, Murray Gell-Mann working in America and Kazuhiko Nishijima working in Japan suggested that all elementary particles should be characterized by a new property named *strangeness* S (see the Table 2).

Table 2

STRANGENESS OF ELEMENTARY PARTICLES

	$S=-3$	$S=-2$	$S=-1$	$S=0$	$S=1$	$S=2$	$S=3$
Particles	Ω^-	$\Xi^0\Xi^-$	Λ^0 $\Sigma^+\Sigma^0\Sigma^-$	π^+pn $\pi^0\eta^0$	K^+K^0		
Anti-particles			$\overline{K}^0\overline{K}^-$	$\overline{\pi}\overline{p}\overline{n}$	$\overline{\Lambda}^0$ $\overline{\Sigma}^+\overline{\Sigma}^0\overline{\Sigma}^-$	$\overline{\Xi}^0\overline{\Xi}^-$	$\overline{\Omega}^-$

It turns out that for all interactions except for the weak ones (that is, when electrons and neutrons are involved) the *law of conservation of strangeness* is valid.

It is worthwhile here to introduce two new notions, baryons and leptons. The *baryon* is an elementary particle (except the negative tau -particle τ^-) whose mass is no less than that of the proton. The particles that have the weak nuclear force between them are called *leptons*. With this in mind, we can move a little further. It has been found, namely, that in all processes involving baryons, their number remains unchanged. To account for this fact, still another "charge" is worth introducing, the baryon charge B. Its value is zero for photons, leptons and mesons and it is $+1$ for baryons and -1 for anti-baryons. The conservation of baryons in transmutations of elementary particles may then be interpreted as the consequence of the *law of baryon charge conservation.* Another property of major importance in elementary particle physics is the *hypercharge* Y, the sum of the baryon charge B and the strangeness S:

$$Y = B + S.$$

A formula have been found that links together all the "charges" we have introduced and applies for any kind of mesons or baryons:

$$Q = I_\xi + \frac{Y}{2} = I_\xi + \frac{B+S}{2},$$

where Q is our old usual simple and familiar charge (+1 for protons, for example). This relationship, known as the Gell-Mann-Nishijima formula, makes the new properties of elementary particles all the more valuable and their introduction—justifiable.

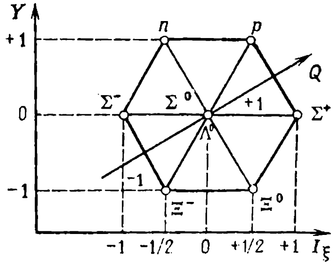

Fig. 57

Let us try to arrange in the I_ξ - Y plane all the baryons with a spin of 1/2. It is easily seen that the octet of baryons forms on this plane a regular hexagon (Fig. 57), with six baryons at the apices and two at the center of it. An exactly the same hexagon is formed by the octet of baryons with zero spin (see Fig. 58). As to what all this means, however, we have no definite answer as yet. But it seems somehow from these geometrically perfect figures that some still unknown fundamental symmetry must exist in nature, some latent connection between the particles belonging to different isotopic multiplets and possessing different values of strangeness. The future will show, what symmetry and what connection. There is still much more to see and learn on the path that started with the discovery of the proton and neutron.

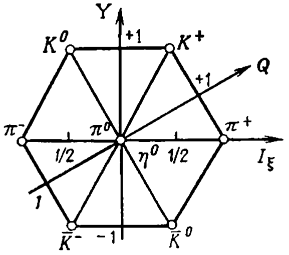

Fig. 58

EPILOGUE

An Endless Road

Studying the universal constants and their physical meaning, you have learnt a good deal about the properties of the world around us. It will perhaps surprise you to know that these constants themselves present one of the most serious problems still to be solved.

Why, I hear you asking, doesn't the author speak of the fundamental constants entering the most important laws of physics? What problems may there be? And if so, what is the book written for, after all, if these constants still remain an open question for the reader? Well, these are quite natural questions, of course. Let me try to answer.

How many constants? In this book, we have confined ourselves to those constants only that are discussed in school textbooks. In all, we have seen 11 of them. But certainly the school courses do not comprise all of modern physics and for those interested there is much more to be studied. And there are actually much more constants than we have told you about.

But how many? This is a question that long worries scientists and so far has no definite answer. What bothers physicists in particular, is that some of the constants are related to the microworld and some to the macroworld. There is something wrong about this division, for it contradicts to the unity of Nature. It is believed, therefore, that some links should exist between the two types of constants, and in some cases such links have indeed been found. For example, the universal gas constant R is expressed in terms of Boltzmann's constant k and Avogadro's number N_A. One should also expect that some of the microworld constants are to be somehow linked with one another. So far, however, these latent connections are not discovered. To discover them, to find ways of united description of Nature—this is a task for the future.

Why are the constants not deduced from theory? This is another uncertain question. Why is it that the values of the constants are not obtained theoretically and should be measured experimentally, sometimes with enormous difficulties? At present, we only have to put up with the way things are. But certainly the edifice of physics cannot be completed until this problem is solved.

One way out has been suggested by Albert Einstein. We have got used, he points out, to express physical constants in arbitrary units. The speed of light, for example, in meters per second. What Einstein proposes is to get rid of dimensional constants and replace them by dimensionless ones (which are the ratios of, for example, one mass to another, one speed to another and so on). He wrote in his autobiographical notes: "If one considers this done, then only "dimensionless" constants could occur in the basic equations of physics... nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory)."

Are the constants constant? The age of our Universe has been estimated to be 10-12 billion years old or about 10^{17} seconds. Neither a year nor a second, however, are the fundamental quantities in the Universe ("Nature knows nothing about them"). As a more appropriate time unit, it is reasonable to take the ratio of 10^{-12} cm (which is a typical size of an elementary particle) to the speed of light 3×10^{10} cm/s. This is about 10^{-23} s and with this unit the dimensionless age of the Universe becomes 10^{40}. Now, the ratio of the electromagnetic force to the gravitational force, as theoreticians tell us, is also 10^{40}. Is this a mere coincidence or some serious hint?

It turns out that this is not the only coincidence of this kind. Let us calculate, for example, the ratio of the size of the Metagalaxy, about 10^{28} cm, to that of an elementary particle. Curiously enough it is 10^{40} again. P. A. M. Dirac, whom we have already met on these pages, concluded from this that, as time goes on, the gravitational interaction weakens. Not too rapidly, though (to put it mildly), by about one ten-billionth per year. Today, this is by far beyond the limits of measurement accuracy available, but let us wait and see.

It so happens that we again end up with unresolved questions. If the reader is waiting for the happy end, he (or she) may well be dissatisfied. But take heart. Physicists are in a constant search for new theories and are quite certain as to the direction of future research. It becomes increasingly clear that a new science will be much more than a mere improvement of the old one. A new kind of physics is now being created, which will be able to produce a unified theory of natural world. It will explain the nature of space and time and link together both the boundless Cosmos and its unimaginably small building blocks, elementary particles. Perhaps we are at the threshold of a new revolution of ideas, much more radical than those caused by Newton and Einstein. Is there anything so wonderful and fascinating as these continuous never-to-end attacks on the strongholds of Nature? Let me end this book with wise and profound words of great Einstein: "*Undoubtedly, the mind seems to us feeble when we are thinking of the problems it is supposed to solve, especially so when it is contrasted with the madness and passions of mankind which, admittedly, rule human lives in both small and great things. Still the creations of intellect outlive the noisy fuss of generations and illuminate the world for centuries with light and warmth.*"

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THE FASTEST SPEED

by S. Filonovich, Cand. Sc. (Phys.-Math.)

The constant denoting the velocity of light in a vacuum is encountered in every branch of physics, and this universality brings out the unity of the physical world. Although it is now over three hundred years since the constant was first defined it yielded to scientific assaults only slowly, revealing as it did unexpectedly new phenomena. Its universality and the surprises that it threw up make any attempt to relate how the velocity of light came to be measured a minor history of physics. This book therefore explains the requisite science against the background of the historical personalities involved. Intended for teachers and school pupils.

The stern academical title of the book is somewhat misguiding for this is, in fact, a fresh and exciting account of physics, tracing its experimental and conceptual development from the ancient Greeks up to the present day. In thorough studies and heated scientific controversies, it was through the endeavours of many remarkable men that the profound physical significance of the universal physical constants was revealed, sometimes with a complete revision of old views and formation of new physical disciplines. O. P. Spiridonov's *Universal Physical Constants* appears to be the first book, both in the USSR and abroad, to be specifically concerned with a systematic discussion of the constants. A "case history" is given for each of them. In telling the story, the author places strong emphasis on logical continuity and the lucidity of his style is never achieved at the expense of scientific strictness.